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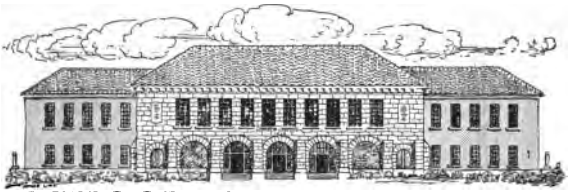

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ELEMENTS OF PHYSICS

BY

FERNANDO SANFORD

Professor in Leland Stanford Junior University

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PREFACE

"MAN may have at his fingers' ends all the accomplished results and all the current opinions of any one or of all the branches of science, and yet remain wholly unscientific in mind; but no one can have carried out even the humblest research without the spirit of science in some measure resting upon him. And that spirit may in part be caught even without entering upon an actual investigation in search of a new truth. The learner may be led to old truths, even the oldest, in more ways than one. He may be brought abruptly to a truth in its finished form, coming straight to it like a thief climbing over the wall; and the hurry and press of modern life tempt many to adopt this quicker way. Or he may be more slowly guided along the path by which the truth was reached by him who first laid hold of it. It is by this latter way of learning the truth, and by this alone, that the learner may hope to catch something at least of the spirit of the scientific inquirer."*

THREE hundred years ago a new method of acquiring knowledge was given to the world by Gilbert, in England, and by Galileo, in Italy. When this method was adopted by investigators, Physical Science was still in its infancy, while other branches of human knowledge, as Philosophy, Literature, and Art, had apparently reached their highest possible achievements. Since that time, the development of Physical Science

* From the Presidential Address by Sir Michael Foster, K.C.B., F.R.S., to the British Association for the Advancement of Science, Dover, Sept. 13, 1899.

has been the most remarkable phenomenon of the world's history.

This new method of acquiring knowledge, which may be called the scientific method, has been often discussed, and there is substantial agreement as to the steps which it involves. They are: (1) The acquisition of individual facts, either by general observation or by the method of artificial observation known as experimentation; (2) Generalization, the statement of a general relation which seems to exist between these individual facts; (3) Deduction, the making of individual inferences based upon the generalization of the second step; and (4) Experimentation to test the accuracy of these inferences. A method which starts in the middle of the process by stating the generalization and requiring the pupil to make the deductions only, may give a good training in deductive reasoning —in Algebra and Geometry—but it cannot teach Physics nor give a training in the methods of Physics. A method which makes the generalizations and deductions and calls upon the pupil to verify these deductions by experiment likewise gives training in but one step of the process. And a method which teaches the subject-matter of Physics from the text-book alone and provides a list of unrelated experiments to be performed for the purpose of training the observing powers or giving skill in manipulation misses the whole process.

The present text-book is a result of the attempt of the writer to apply this scientific method in all its steps to the teaching of Physics. It does not contain as many laboratory experiments as are recommended in some books, but most of those it does contain are vital to the successful teaching of the book. No ex-

periments are admitted for any reason except that they are needed for teaching the subject as outlined. Accordingly, they are not selected because they are quantitative or qualitative in character, or because they are easy or difficult to perform. The lecture-room method of imparting knowledge is believed by the writer to be the poorest of all methods with elementary students, and the book is not prepared with the idea that it will need supplementing by a lecture course. Neither is it intended to dispense with the services of a teacher. In fact, it has been prepared especially for the teacher who has had an adequate training in the physical laboratory, and it is not likely to succeed with any other teacher.

In the arrangement of the subject-matter a considerable departure has been made from the order of other books, but this arrangement has not been adopted without careful tests by the writer and others. The great distinction between the Physics of the present and that of the past generation lies in the substitution of the concept of energy for the old notion of forces. The attempt is here made to base Mechanics upon the energy concept from the beginning, and to assign to the notion of force the meaning which it holds in modern Physics. In the treatment of the properties of bodies, the order adopted seems justified by the relative simplicity of the gaseous state of aggregation as compared with the liquid or solid state. Here, too, more stress is laid on the kinetic gas theory than is usual in an elementary text-book, but this seems to be warranted by the great importance of the theory in modern Physics and its bearing on the modern theory of Heat.

The greatest departure from established usage in

elementary text-books has been made in the subject of Optics. Here the attempt has been made to develop the Geometrical Optics from the beginning without making use of the fiction of rectilinear propagation. In the writer's own experience, this greatly simplifies the subject, especially in the study of Refraction. While the experiments on interference are not usually given in a high-school course, they offer no greater difficulties to the pupil than the ordinary experiments in other subjects, and they are essential to an understanding of the undulatory theory of Light. The experiments on the measurement of wave-length in both Sound and Light have seemed to the writer a very important part of the course. The treatment here given to the subject of the refractive index has also been justified by its use for several years with the writer's own pupils.

While the course as here outlined cannot be taught without a suitably equipped laboratory, it is believed that the necessary expense of fitting up a laboratory for its teaching is as small as for any other laboratory course of high-school grade which has been suggested.

F. S.

LELAND STANFORD JUNIOR UNIVERSITY,
June 7, 1902.

Mech 135
Ed in 92
227
55%

Heat 62
Sound 38
Light 83
183
45%

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PHYSICS

PART I

MECHANICS

FUNDAMENTAL DEFINITIONS

Physics.—Physics is the science which treats of the changes that take place in the physical universe.

The Physical Universe.—The physical universe is that part of the universe which is, so far as we know, made up of the two fundamental existences, Matter and Energy.

Matter.—No complete definition of matter is possible. We may learn of the properties of material bodies, but the essential nature of matter is entirely unknown to us. The name is generally understood to mean the indestructible substance of all bodies which are appreciable by our senses.

Energy.—The essential nature of energy is likewise unknown. We can measure its quantity, but we know nothing of its descriptive qualities. It may be provisionally defined as the capacity for doing work.

Work.—The term work, as used in Physics, may be defined as the producing of such changes in the relative positions or relative motions of material bodies as would require an effort on our part to produce. Thus we do work upon a stone when we lift it from the

ground or when we throw it. In the one case we have produced a change in the relative positions of the stone and surrounding objects; in the other case we have changed the velocity of the stone with reference to surrounding objects.

An effort which does not produce a change in either the relative positions or the relative velocities of material bodies or the material particles of which they are composed does not result in work. Thus it may require a great effort to hold a heavy stone supported above the earth, but as long as the stone is held in a fixed position relative to the earth, no work, in the physical sense, is done upon it.

Measurement of Work.—Work is generally measured by the energy expended in lifting a body of known weight through a given vertical distance above the earth. Thus to lift a pound weight one foot high is to do one foot-pound of work, and requires the expenditure of one foot-pound of energy. To lift two pound weights one foot high or one pound weight two feet high is to do two foot-pounds of work.

MACHINES

Definition.—A machine is an instrument by which energy is applied to the performance of work.

The Lever.

LABORATORY EXERCISE 1.—A uniform wooden bar four or five feet long should be so balanced on a horizontal axis through its middle point that it will remain in equilibrium when inclined at any angle to the horizontal. It should be placed in front of a wall or vertical board ruled in horizontal lines one inch apart, or a yardstick ruled in inches may be supported vertically back of each end of the bar as shown in Fig. 1.

Suspend a one-pound weight from one end of the bar, and

taking hold of the bar with the hand turn it on its axis until the weight has been raised one foot.

How much work have you done upon the weight?

Is the amount of work done upon the weight the same no matter where you take hold of the bar?

Suspend a pound weight near the other end of the bar where it will be raised by the falling of the first weight when the bar is released.

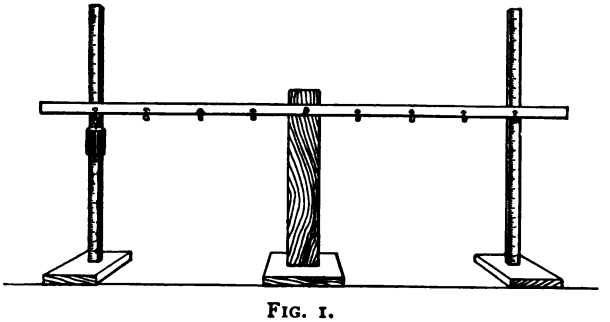


FIG. 1.

In raising the first weight work was done upon it. By virtue of this work, the weight was raised into a position where it had more energy than it had before. This energy, we have seen, may be used in raising another weight on the other end of the bar.

Place the second weight at the same distance from the axis as the first weight. It will then be raised as far as the first weight falls, and will acquire energy as fast as the first weight loses it. Will either weight raise the other under these conditions?

State the conditions of equilibrium for two equal weights on the bar.

Balance a one-pound weight on one side of the axis by a half-pound weight on the other side. What of the distances through which the two weights move when the bar is turned? Compare the energy gained on one side with the energy lost on the other side.

State the conditions of equilibrium for unequal weights on the bar:

(*a*) In terms of the gain or loss of energy on each side.

(*b*) In terms of the products of the weights into the respective distances through which they move.

(*c*) In terms of the products of the weights into their respective distances from the axis of the bar.

The Lever as a Machine.—A rigid bar supported as above on an axis about which it may turn may be used to raise weights or to move heavy bodies. When so used, it becomes a machine, and is called a Lever.

The axis upon which the lever turns is called the Fulcrum.

The arm upon which the weight is raised or by which the work is done is called the Work Arm.

The arm to which the energy is applied to do the work is called the Power Arm.

Since both the weight and the energy which moves it may act on the same side of the fulcrum, the same part of the lever may belong to both the power arm and the work arm.

Classes of Levers.—When the lever has its fulcrum between the power arm and the work arm, it is called a lever of the first class.

When the weight to be raised or the body to be moved is between the point of application of the energy and the fulcrum, it is called a lever of the second class.

When the energy is applied between the weight and the fulcrum, it becomes a lever of the third class.

Make diagrams illustrating the three classes of levers.

To which class of levers does the nut-cracker belong? The common fire-tongs? The wheelbarrow?

Most of the movements of our bodies are performed by means of levers. Fig. 2 shows the bones of the arm with the biceps muscle attached. To which class

of levers does the forearm belong when it is being bent upon the arm ?

FIG. 2.

Moment.—The product of the weight or power into its perpendicular distance from the fulcrum is called its Moment.

State the conditions of equilibrium of a lever of the first class in terms of the moments of its power and weight.

Mechanical Advantage.—We have seen that no work is saved by the use of a lever. The same amount of energy must be used to do a given quantity of work with any lever. By means of a lever, however, one may do work which he could not possibly do without it. Thus a man who can lift only two hundred pounds may lift a thousand pounds with a lever. In this case the lever is said to give him a mechanical advantage of five; i.e., by means of it he can lift five times as much as he could without it.

When a weight of one pound on one arm of a lever balances a weight of twelve pounds on the other arm, the lever is said to give the lighter weight a mechanical advantage of twelve.

In general, the ratio of the weight upon which the

work is done to the weight doing the work is called the mechanical advantage of the lever.

PROBLEMS.—State the mechanical advantage of a lever in terms of the distances travelled by the power and weight.

What is the mechanical advantage of a lever in which the work arm is two feet long and the power arm three feet long?

The Fixed Pulley.

LABORATORY EXERCISE 2.—Attach a pulley* to a support two or three feet above the table and suspend a pound weight by a cord passed over the pulley and held in the hand. Pull on the cord and raise the weight one foot. Through what distance does your hand move? Is there any mechanical advantage in a fixed pulley? What weight must be attached to the string to balance the pound weight? When the weights are in equilibrium, will one always gain energy as fast as the other loses it?

Show how the fixed pulley may be regarded as a lever. To which class of levers does it belong?

Levers of the Second and Third Classes.

LABORATORY EXERCISE 3.—Place the fixed pulley above one end of a lever mounted as in Fig. 3. Attach one end of the cord to the end of the lever, hang a pound weight on the other end of the cord and balance it by weights suspended from the lever between the cord and the fulcrum. When the weights are in equilibrium, turn the pulley until the pound weight has lost one foot-pound of energy. How much energy has been gained by the weights on the bar?

State the conditions of equilibrium for a lever of the second class in terms of the energy expended and the work accomplished. Do the other conditions of equilibrium in the lever of the first class apply to the lever of the second class?

Attach the cord to the lever near the fulcrum, hang a pound weight near the end of the bar and balance by weights on the other end of the cord. State the conditions of equilibrium in a lever of the third class.

* In all of the pulleys used in the experiments here given the axles should turn in their bearings with very little friction.

Assuming the work to be done in raising the weights attached to the bar and the energy to be applied by means of

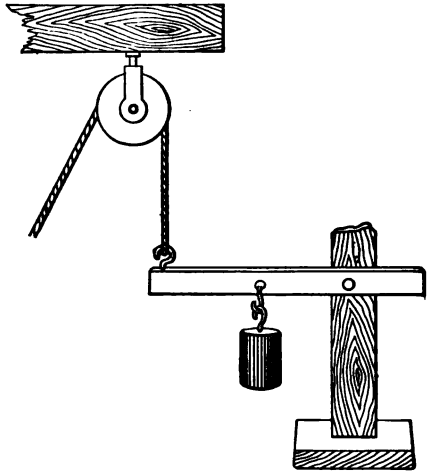


FIG. 3.

the cord, tell in which of the two classes of levers there is a mechanical advantage.

The Movable Pulley.

LABORATORY EXERCISE 4.—Suspend a weight from a movable pulley which is supported by a cord attached at one end and passing around the movable pulley is carried upward and over a fixed pulley, as shown in Fig. 4. Balance the movable pulley and weight by weights attached to the free end of the cord. Regarding the weight of the movable pulley as a part of the weight to be raised, what is its mechanical advantage?

Systems of Pulleys.—Many possible combinations of pulleys may be made. A common method of using several pulleys with a single cord is to mount a number of pulleys side by side in the same frame so that they may all turn on the same axle. Two such sets of pulleys are used together, the one being attached to

the support and the other to the weight, and a single cord is passed around all the pulleys as in Fig. 5. Such an arrangement is known as a block and tackle.

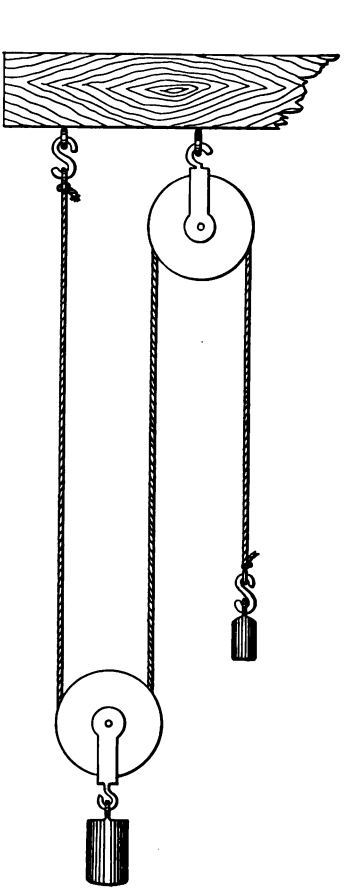


FIG. 4.

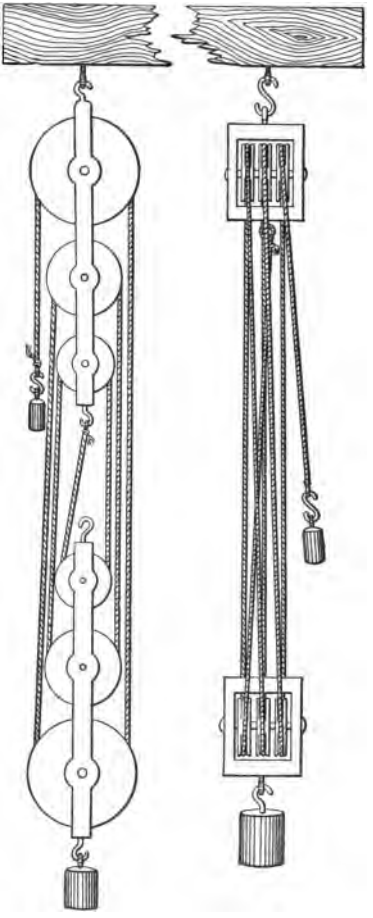


FIG. 5.

Mechanical Advantage of Systems of Pulleys.

LABORATORY EXERCISE 5.—It is said that the mechanical

advantage of any system of pulleys using a single cord is numerically equal to the number of parts of the cord which support the weight. Arrange a system of fixed and movable pulleys and test this statement. Give a diagram of the system used.

The Inclined Plane.—In raising or lowering heavy bodies they are often wheeled or rolled up or down a rigid plane surface inclined at an angle to the horizontal. Thus, in loading barrels into a wagon they are frequently rolled up a plank, one end of which rests upon the ground and one upon the wagon. When used in this way, the plank becomes a machine, and is called an inclined plane.

LABORATORY EXERCISE 6.—An inclined plane made of a smooth board is provided with a fixed pulley at its upper

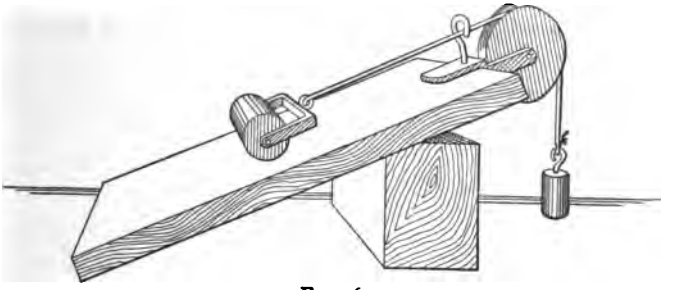


FIG. 6.

end. Place a loaded car or roller on the inclined plane, and support it by weights suspended from a cord passed over the fixed pulley and running parallel to the plane.

Can you support a heavy weight upon the plane by a lighter weight upon the cord?

When the weights are in equilibrium, pull on the string and determine the vertical distance through which each weight moves. Knowing the value of the two weights, determine if one gains energy at the same rate that the other loses it.

How much work is required to raise a five-pound weight one foot high on an inclined plane, disregarding the friction

on the plane? Will the work be the same on a plane inclined at any angle to the horizontal? Prove your statement for different inclinations of your plane.

State the conditions of equilibrium for two weights, one of which is supported on the plane and the other on the cord, in terms of the gain or loss of energy of each weight when they are moved.

Prove that to raise the heavy weight the height of the plane the light weight must fall the length of the plane.

In the case of equilibrium, what relation holds between the two weights and the height and length of the plane?

State the mechanical advantage of the inclined plane in terms of the height and length of the plane.

If the supporting cord were kept parallel to the base of the plane, how far would the lighter weight fall in raising the heavy weight the height of the plane? What would be the mechanical advantage of an inclined plane used in this way?

Modifications of Lever, Pulley, and Inclined Plane.—Many modifications of the lever and pulley and inclined plane are used in mechanical work. Some of the best-known forms are the Wheel and Axle, Windlass, Capstan, and Screw.

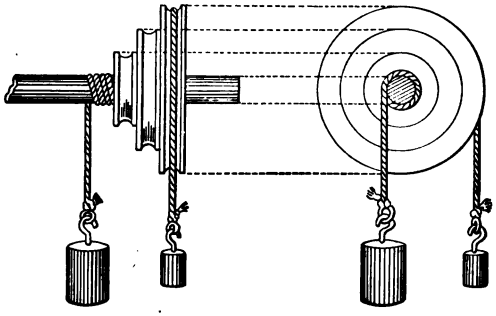


FIG. 7.

The Wheel and Axle.—The wheel and axle consists of two fixed pulleys rigidly attached to each other and turning upon the same axis. The larger of these is

called the wheel, and the smaller, which is generally in the form of a cylinder, is called the axle. The weight to be raised is attached to a cord which is wound up on the axle by unwinding another cord from the wheel.

State the mechanical advantage of the wheel and axle in terms of the radii of the two pulleys.

The Windlass.—The windlass is an arrangement similar to the wheel and axle, in which the wheel is replaced by a crank, or by spokes for turning by hand. The Capstan is a form of the same machine frequently used on shipboard. The cylinder around which the cord is wound is vertical, instead of horizontal, and is generally turned by levers called capstan bars which are thrust into holes made for them in the cylinder.

The Screw. — The screw is a machine frequently used for raising heavy weights or for exerting great pressures. It is equivalent to a long inclined plane wound around a cylinder. The power is frequently applied to a long lever attached to the screw. The mechanical advantage of the screw is theoretically the same as in other machines, that is, the ratio of the distance travelled by the power to the distance through which the weight is moved. In practice the friction is considerable, and the mechanical advantage is always less than its theoretical value.

The Pitch of a screw is the distance between two contiguous threads, and is, accordingly, the distance travelled by the weight for each revolution of the screw.

POWER

Definition.—The Power of a machine is the rate at which it is capable of doing work. The unit of power

in most common use in our country (though another unit to be described later is coming into general use) is called the Horse-power. It is the rate of doing work equivalent to 33,000 foot-pounds per minute. Thus a machine of two horse-power is capable of doing 1100 foot-pounds of work per second. Steam engines are usually rated in horse-powers.

EFFICIENCY

Definition.—In every machine some of the energy is used in doing useless work against friction or other resistances. The ratio of the useful work done by the machine to the total work done upon it is called the efficiency of the machine.

PROBLEMS.—If a weight of 10 lbs. must be suspended upon one side of a fixed pulley to just raise a weight of 8 lbs. on the other side, the efficiency of the pulley is .8, or 80 per cent.

If one fourth of the work done upon a screw is used in overcoming the friction, what is the percentage of efficiency of the screw?

GEARING

Use of Gearing.—It is often convenient in practice to transmit power from one shaft to another. This is accomplished by means of belting, chain gearing, cog gearing, and the like.

PROBLEMS.—In the cog gearing shown in Fig. 8 the smaller wheel has 16 cogs and the larger 46. What is the mechanical advantage of power applied to the axle of the smaller wheel?

If the crank-arm attached to the smaller wheel is 16 inches long and the axle of the larger wheel is 4 inches in diameter, what is the mechanical advantage of the combination when used to raise a weight by winding a cord on the axle of the larger wheel?

A machine is driven by a belt from a power-shaft making

three revolutions a second. The belt wheel on the power shaft is two feet in diameter and that on the driving shaft of the machine is eight inches in diameter; how many revolutions a second does the driving shaft make?

The front sprocket-wheel of a bicycle has 30 teeth and the rear sprocket has 12. If the wheels are 28 inches in diameter, how far does the bicycle travel for one revolution of the pedal cranks?

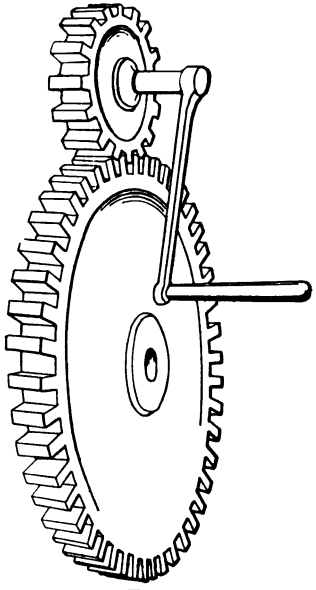


FIG. 8.

The "gear" of a bicycle is expressed in terms of the diameter in inches of a wheel which would travel as far in one revolution as the geared bicycle travels in one revolution of the pedal cranks. Thus a bicycle having a 28-inch driving wheel, a front sprocket with 24 teeth and a rear sprocket of 8 teeth is geared so that it is equivalent to an ungeared, or "ordinary," bicycle having a driving wheel 84 inches in diameter, and is known as an 84-gear wheel.

What is the gear of the bicycle described in the preceding problem?

CENTER OF GRAVITY

Definition.—In our experiments with the lever, the bar was so balanced upon a pivot that it would remain at rest when turned into any position. It is plain that if the pivot had been at one end of the bar, the bar would have remained at rest only in a vertical position. If the pivot were at a point near one end, the bar could be balanced in a horizontal position only by means of

a weight attached to its short end. The bar accordingly has a moment, and since a lever can be in equilibrium only when the moments of the weights on opposite sides of the fulcrum are equal to each other, the moment of the weight attached to the short end of the bar must equal the moment which the bar itself has on the other side of the fulcrum. The point in the bar about which its weight moments on opposite sides are always equal is generally called the Center of Gravity or the Center of Mass of the bar. Neither of these terms expresses the true meaning of the position of the point, since in an irregular body the weights on opposite sides of the center of gravity may be very unequal.

To Find the Center of Gravity of an Irregular Solid.

LABORATORY EXERCISE 7.—An irregular board two or three feet long and of uniform thickness has a number of small holes bored straight through it. A stiff wire or knitting-needle is driven horizontally into a rigid support, and the board is suspended by slipping one of the holes over this pivot. When the board comes to rest, the weight moments on opposite sides of a vertical line through the pivot must be equal, hence the center of gravity must be in this vertical line. By means of a plumb line made by attaching a bullet or other heavy body to a thread, mark on the board the vertical line through the pivot.

Place another hole on the pivot and repeat the operation. The two lines should cross at a point opposite the center of gravity of the board. Do the lines drawn from all the holes cross at the same point?

If there is not a hole through the center of gravity, bore one and place this hole on the pivot. Are the weight moments on opposite sides of this hole equal with the board turned in any position?

To Find the Weight Moment of a Bar Supported from a Point Outside its Center of Gravity.

LABORATORY EXERCISE 8.—Select a wooden bar two or

three feet long, preferably not of uniform size, weigh it on the platform scales, and determine and mark the position of its center of gravity. (The piece of board used for the former experiment may also be used for this one.) Suspend the bar from a pivot, at some distance from its center of gravity. Attach a weight equal to the weight of the bar in such a position on the bar that the bar will remain in equilibrium in a horizontal position. Measure the distances from the pivot to the suspended weight and to the center of gravity of the bar. How do these distances compare?

Support the bar at another distance from its center of gravity, and measure off the distance from the pivot at which the weight must be attached in order to produce equilibrium in a horizontal position. Attach the weight and see if your conclusion is correct.

Define the moment of a lever in terms of its weight and the distance between its center of gravity and the fulcrum.

A bar weighing 10 pounds is suspended from a pivot three feet from its center of gravity; what is its moment? What work must be done upon the bar to raise its center of gravity two feet? How does this compare with the work which must be done to raise the whole bar two feet?

A lever weighing 20 pounds is balanced by a weight of 5 pounds placed 4 feet from the fulcrum; how far is the fulcrum from the center of gravity of the lever?

STABILITY

Conditions of Equilibrium.—We have seen that the weight moments of a body are always equal on opposite sides of its center of gravity, hence that when the center of gravity is supported the body is in equilibrium.

Stable and Unstable Equilibrium.—When a body is so supported that when disturbed it tends to return to its former position of rest the body is said to be in Stable Equilibrium. If a slight disturbance causes it to seek a new position of rest, it is said to be in Unstable Equilibrium.

Neutral Equilibrium.—A body supported on a pivot through its center of gravity, or a homogeneous sphere resting on a level surface, is said to be in Neutral Equilibrium, because it remains at rest equally well in any position into which it may be turned.

Examples.—A body supported on a pivot directly above its center of gravity is in stable equilibrium, since when it is turned into any other position the moment of the body will cause its center of gravity to fall back to its original position. If the same body be balanced with its center of gravity directly above the pivot, it may remain at rest; but if disturbed, its center of gravity will fall to the stable position below the pivot.

If a vertical line through the center of gravity falls outside of the support of the body, the body will not be in equilibrium unless held in this position by other bodies.

Why can you not stand on one foot with its side against the wall of the room?

Measure of Stability.—The stability of any body resting on a surface may be estimated from the amount of work required to overturn the body.

PROBLEMS.—A homogeneous cube four feet on each edge is resting on one face on a horizontal surface; how high must its center of gravity be raised before the cube can be overturned? If the cube weighs ten pounds, how much work must be done to overturn it?

A brick measuring 8 by 4 by $2\frac{1}{2}$ inches weighs 5 pounds. When resting on a level surface, how much work is required to overturn it from each of its faces?

A load of hay and wagon weighs two tons. If the wagon wheels are four feet apart and the center of gravity of the load is six feet high, how much work is required to overturn it on level ground?

THE PENDULUM

Energy of a Swinging Pendulum.

LABORATORY EXERCISE 9.—Prepare a pendulum by attaching a thread or soft cord three or four feet long to a heavy

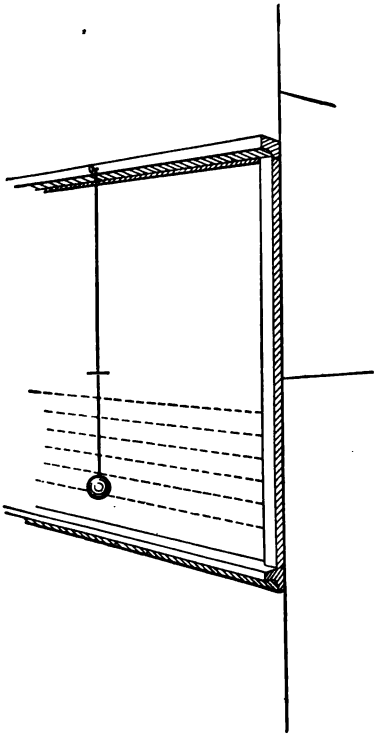


FIG. 9.

lead or iron ball. Attach the other end of the thread to a clamp or a long nail driven into the wall so that the pendulum will swing only an inch or two from a vertical wall. Rule the space back of the pendulum in horizontal lines at equal distances apart,

Draw the ball to one side so that it shall be at the same height as one of the lines, and release it so that it will swing parallel to the wall. Note the height to which it rises on the other side of its arc.

Repeat several times, raising the pendulum to a different height each time.

Does the pendulum acquire sufficient energy in falling through one half its arc to raise it again to the same vertical height from which it has fallen?

Drive a knitting-needle or long nail into the wall directly below the point of support of the pendulum, and at a distance of a foot or more above the pendulum ball. Draw the ball to one side as before, and let it swing so that the thread will strike the knitting-needle just as the ball reaches its lowest point. It will now swing upward through a different arc from the one through which it has fallen. Does it rise to the same height as before?

Does the energy acquired by a pendulum in falling through one half of its arc depend upon the length of the arc, or upon the vertical height through which it falls?

State the same proposition with reference to a ball rolling down an inclined plane.

Potential and Kinetic Energy of the Pendulum.— In our previous experiments we have found that the energy which a body has may depend upon its vertical height above the earth, or above any horizontal plane to which its energy is referred. We now see that the pendulum ball when at its lowest point has energy sufficient to raise it again to the height from which it fell in acquiring this energy. A moving body may accordingly have energy which is not due to its position with reference to other bodies.

The energy which a body has on account of its position is called Potential Energy.

That part of the energy of a moving body which is not due to its position is called Kinetic Energy.

When the pendulum ball is at the lowest point of its arc, its energy, considered as a pendulum, is all kinetic. It may still have potential energy on account of its height above the earth, but this energy cannot be changed into work so long as it remains attached to the support.

When the ball is at the end of its swing it stops for an instant before turning back. At this instant its energy is all potential. Since its kinetic energy at the lowest point of its arc is sufficient to give it again as much potential energy as it had at the highest point, these two quantities of energy must be equivalent to each other. When it is falling, it is losing potential energy and gaining kinetic. When it is rising, it is losing kinetic energy and gaining potential. When the one kind has changed entirely to the other kind, the total quantity of energy is still the same. When it loses one kind of energy, the pendulum ball must accordingly gain the other kind at the same rate. If it gave off no energy to other bodies, its total energy would remain forever the same, though constantly changing from one kind to the other. In practice, it does work in setting the air around it in motion, and in setting up vibrations in its support, which can never be absolutely rigid, and hence its energy is slowly given off to other bodies, so that the energy of each succeeding vibration is slightly less than that of the preceding one. If the ball is very heavy and the thread very flexible, the rate of decrease is small and cannot be perceived in a single vibration. It is believed that no body which has energy can lose it except by giving it off to some other body.

Isochronism of the Pendulum.

LABORATORY EXERCISE 10.—Suspend a heavy pendulum two or three feet long in front of a plumb line or vertical mark on the wall,* and find its time of vibration as follows:

Set the pendulum swinging through an arc of only two or three inches, and placing the eye in a line with the vertical mark and the pendulum when at rest, note with a watch or clock provided with a second-hand the exact instant of the transit of the pendulum ball across this mark. Record this time to the nearest half-second, and count fifty successive transits of the pendulum ball *in the same direction*, noting accurately the time of the fiftieth. This can be done more accurately if one observer will count aloud the transits, signalling the time of each by tapping on the table with a pencil, while another observer reads the time from the clock.

The interval between the first and the fiftieth transit divided by forty-nine will give the time of one complete vibration of the pendulum.

Make five determinations of this time of vibration, using arcs of nearly the same length. What is the average time of vibration from the five sets? What is the greatest variation from this time in any set?

Make five determinations of the time of vibration with the pendulum swinging through an arc of a foot or more.

Does the pendulum swing more quickly through a long, or a short arc?

Is the time of vibration constant for small arcs? What use is made of this property of the pendulum?

Relation of Time of Vibration to Length of Pendulum.

LABORATORY EXERCISE 11. — Prepare three pendulums respectively 36, 25, and 16 inches long, measuring from the point where the thread is clamped to the support to the center of the ball, and find their times of vibration as before.

*Care should be taken that the thread is held tightly exactly at the point of suspension, and that it does not touch anything below this point. A good method of suspension is to draw the thread through a vertical hole in the support and fasten it by a plug driven in from below and cut off flush with the support.

Test the statement, "The times of vibration of different pendulums are related as the square roots of their lengths."

How long must a pendulum be made in order to vibrate in half the time of a pendulum 36 inches long? To vibrate in one third the time?

Relation of Time of Vibration to Weight and Material of Pendulum.

LABORATORY EXERCISE 12.—Using pendulums of the same length but with balls of different material, find if the time of vibration depends upon the weight or material of the pendulum, or only upon its length. Describe the pendulums used, and give their times of vibration.

The Seconds Pendulum.—The Seconds Pendulum is a pendulum of such length that it swings once across its arc in one second, and accordingly makes one complete vibration in two seconds. Such a pendulum used in a clock will beat seconds.

The length of the seconds pendulum is different upon different parts of the earth. In the latitude of the United States and at sea level it is about 39.13 inches or 99.38 centimeters.

What is the length of the clock pendulum which beats half-seconds?

Simple and Compound Pendulums.—In the pendulums used in the preceding experiments most of the weight has been concentrated in the ball at the end of the thread. In the ideal Simple Pendulum the weight is regarded as being all concentrated at the center of the ball. When the weight is not all concentrated at a single point, but is distributed to different parts of the pendulum, the pendulum is said to be a Compound Pendulum. The time of vibration of a compound pendulum depends not upon its apparent length, but upon the distribution of its weight.

To Find the Equivalent Length of a Compound Pendulum.

LABORATORY EXERCISE 13.—A piece of board two or three feet long and wider at one end than at the other should have two small holes bored straight through it at equal distances from the two ends. By placing these holes over a knitting-needle driven horizontally into a support the board can be made to swing as a compound pendulum.

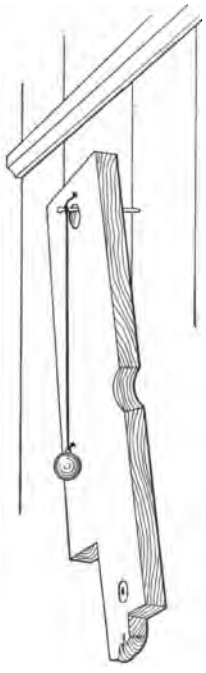


FIG. 10.

Determine the time of vibration of the board when suspended from each end.

Find the length of a simple pendulum which will vibrate in the same time as the board in each case. (Attach the thread of the simple pendulum to the knitting-needle, and adjust its length until the two pendulums will swing in unison.)

Centre of Suspension of a Pendulum.—The position of the axis about which a pendulum swings is called its Center of Suspension. The position of the knitting-needle may be taken as the center of suspension of the compound pendulum.

Centre of Oscillation of a Pendulum.—The point in a compound pendulum at which its weight might all be concentrated without changing its time of vibration is called the Center of Oscillation of the pendulum. This point is found by means of the comparison with the equivalent simple pendulum.

Mark the center of oscillation of the board pendulum for each center of suspension. Does either of the centers of oscillation correspond with the center of gravity?

Length of a Compound Pendulum.—The length of a compound pendulum is regarded as the same as the length of the equivalent simple pendulum. It is accordingly the distance from the center of suspension to the center of oscillation.

PROBLEMS.—Is the length of the compound pendulum the same for different centers of suspension?

Bore a hole through one of the centers of oscillation of the pendulum, and use this point as a center of suspension. How is the time of vibration of a compound pendulum affected by changing its suspension to its center of oscillation? Are the centers of suspension and of oscillation interchangeable in the same pendulum?

A pendulum is made of a long bar provided with two axes so placed that it makes one complete vibration in two seconds when suspended from either axis. How far apart are the axes?

Persistence of Plane of Vibration of a Pendulum.

LABORATORY EXERCISE 14.—Make a pendulum by attaching a heavy weight to a wire and suspend it from a support which can be rotated around a vertical axis. Set the pendulum swinging and turn the support around. Does the plane of vibration of the pendulum rotate with the pendulum?

Drive a knitting-needle straight into the end of a round stick, as a piece of broom-handle. Lay the stick upon the table and holding it down with the hand, set the needle vibrating through as large an arc as possible, and roll the stick along the table. The needle is thus made to rotate; does its plane of vibration also rotate?

Foucault's Pendulum Experiment.—In 1851, Foucault, a French physicist, used this property of the pendulum to show the rotation of the earth. It is plain that a pendulum set swinging in a given meridian

at the Equator would continue to swing in that meridian during an entire rotation of the earth. A pendulum set swinging in a given meridian at the Pole would continue to swing in its original plane, while the meridian would swing completely around in twenty-four hours. To an observer at the Pole, it would seem that the plane of vibration of the pendulum had made a complete rotation in that time. At any position between the Equator and the Pole, the plane of vibration of the pendulum will appear to make a partial rotation in twenty-four hours. At a latitude of 40° this apparent rotation is nearly 10° an hour, and may be easily shown with a long and heavy pendulum.*

GRAVITATION

Definition.—We have seen that all bodies acquire potential energy as they are raised above the earth, and that when unsupported they fall to the earth. Likewise, bodies resting upon the earth exert a pressure upon objects beneath them. The cause of this pressure is entirely unknown to us. It has been named the Gravitation Pressure, or the Force or Attraction of Gravitation. The weight of a body is the measure of the gravitation pressure upon it. A falling body is said to acquire its kinetic energy from the work done upon it by gravitation.

* For this purpose a pendulum weighing several pounds should be suspended by a flexible wire from the ceiling or the highest support attainable. Foucault's original pendulum was 200 feet long, but a pendulum 10 feet long will swing long enough to show the phenomenon. The pendulum ball should be pulled to one side a foot or more, and should be held by a loop of thread fastened to a rigid support. When everything is at rest, the thread should be burned to release the pendulum. It should swing just above a table or a level board on which its original direction of vibration should be carefully marked.

Nature of Gravitation Unknown.—The pendulum swings to the lowest point of its arc under the influence of gravitation. In falling through one half its arc gravitation does work upon it, and its kinetic energy is a measure of this work. In rising through the other half of its arc this kinetic energy is expended in doing work against gravitation. At its highest point it has only the potential energy due to gravitation. Since we do not known the nature of gravitation, we cannot know in what form this potential energy exists, but it is believed to be due to some kind of pressure exerted by an invisible, elastic medium which surrounds the earth and all bodies, and which is called the Ether.

Gravitation and Time of Vibration of a Pendulum.

LABORATORY EXERCISE 15.—Suspend a pendulum made of an iron ball, and determine as before its time of vibration through a very small arc. Place a bar magnet with one of its ends just below the ball when at its lowest point, and determine its time of vibration again through a small arc. The pull of the magnet upon the ball affects the time of vibration of the pendulum somewhat as would an increase of gravitation.

How would an increase of gravitation affect the time of vibration of a pendulum?

The weight of bodies on the earth is greater near the poles than near the Equator; in which place would the time of vibration of a given pendulum be less?

Attach a piece of light elastic cord to the same pendulum and, stretching it downward slightly, determine the time of vibration of the pendulum. Repeat, stretching the cord more. Explain the phenomenon which you have observed.

Light and Heavy Bodies Fall with Same Velocity.—Since an increase of gravitation shortens the time of vibration of a pendulum, it must increase the velocity of the falling pendulum. Hence if gravitation were increased bodies would fall toward the earth more

rapidly. But we saw from experiments in Exercise 12 that all pendulums of the same length have the same time of vibration, regardless of their weight or material. This fact led Galileo to the conclusion that light and heavy bodies fall with the same velocity (though Aristotle had taught otherwise), and he tested his conclusion by dropping light and heavy balls from the top of the leaning tower in Pisa.

The "Guinea and Feather Tube."

LABORATORY EXERCISE 16. — Exhaust the air from a "Guinea and Feather Tube," * and see if light and heavy bodies fall with the same velocity when not retarded by the air.

MASS

Potential Energy of a Body Proportional to its Weight.—We have defined weight as the measure of gravitation upon a body, hence the gravitation pressure must be greater upon a heavy body than upon a light one. Since the heavy body does not fall faster than the light one, it must require more work on the part of gravitation to move the heavier body. In the same manner, it requires the expenditure of more energy to raise the heavier body to a given height against gravi-

* A modification of the Guinea and Feather Tube used in early experiments on falling bodies is made as follows: A glass tube half an inch or more in internal diameter and about three feet long is sealed off smoothly at one end by heating in a flame. A small shot or other heavy body and a piece of light paper are introduced into the tube, which should be carefully dried, and the tube is then heated in a flame near the other end and drawn down to a small neck. It is then attached to an air pump and as much as possible of the air exhausted, after which the neck is sealed off in the flame. (A better tube can be made by first sealing off both ends and then exhausting through a side tube.)

By allowing the shot and paper to rest in one end of the tube and then inverting the tube quickly they can be made to fall the length of the tube without being retarded by the air.

tation. The rate at which bodies acquire potential energy when raised above the earth is proportional to their weight, hence in falling they must acquire kinetic energy in proportion to their weight.

Kinetic Energy of Moving Body Independent of its Weight.—But the kinetic energy which a body has at a given time is not affected by the gravitation pressure upon it, hence is independent of its weight. The kinetic energy of a body may enable it to do work while rising against gravitation, hence in spite of its weight. The heavy fly wheel of an engine can acquire no energy from gravitation, since one half of the wheel is moving against the gravitation attraction as fast as the other half is moving with it. Such a wheel when in rapid motion has a large quantity of kinetic energy and may do a corresponding quantity of work before it is brought to rest.

Definition of Mass.—The capacity which a body has for acquiring kinetic energy accordingly varies just as the weight of the body varies, but it is not caused by the weight of the body. It has been thought to be due to the quantity of matter which the body contains, and this quantity has been called the Mass of the body. The attraction of gravitation, which is the cause of the weight of a body, accordingly varies as the mass of the body; and the capacity which a body has for acquiring kinetic energy also varies as its mass. The potential energy of the bodies which we have been considering depends upon the weight of the bodies; their kinetic energy is independent of their weight, and would be the same if gravitation should cease to act upon them.

Indestructibility of Mass.—The mass of a body is the only known property of the body which cannot be

changed by chemical action. Bodies of various kinds have been sealed in glass tubes and allowed to react chemically upon each other, thus changing all their other physical properties, but their weights and their capacities for acquiring kinetic energy were not appreciably changed.

Relation of Weight to Mass.—Since the mass of a body is commonly accepted as the measure of the quantity of material which it contains, we need to frequently determine the masses of bodies. In common practice this is done by comparing the weights of the bodies with the weights of standard units of mass. Since weight varies with a variation in the gravitation attraction, the weight of the same body may be different under different conditions. Thus the gravitation attraction on the moon is only one sixth of what it is on the earth, and a body transported to the moon would have only one sixth of its weight when on the earth. If two masses which are of the same weight on the earth were transported to the moon, they would still be of the same weight there, hence in the comparison of masses by means of their weight a change of the gravitation attraction would not affect the result.

INERTIA

Definition.—The fact that work must be done upon a body to set it in motion, and that a body in motion cannot stop without doing work upon another body, is sometimes said to be due to the Inertia of the body. A body which requires more work than another to give it the same velocity is said to have more inertia than the other. When used in this sense, inertia means the

same thing as mass. There are no units of inertia, so the inertia of a body is never measured.

FALLING BODIES

Gravitation and Falling Bodies.—Bodies falling freely toward the earth soon acquire a velocity so great as to be difficult of measurement. To overcome this difficulty and make observation more convenient various devices are used for slowing down their motion. One such device is to allow the body in the form of a ball or cylinder to roll down an inclined plane. We have seen that it requires the same amount of work to raise a body to a given height on any inclined plane, consequently gravitation will do the same amount of work on a body rolling from the same vertical height down any inclined plane. The velocity which the body will have at the foot of the plane will accordingly depend only upon the height of the plane, and not at all upon its length. By making the plane very long as compared with its height the ball will roll down it very slowly, and the space passed through in successive periods of time can be measured. This device for studying the laws of falling bodies was first used by Galileo.

Atwood's Machine.—Another device in common use in studying the laws of falling bodies is to compel the falling body to raise another body almost equal to itself in weight. In this way, most of its potential energy is transferred to the other body, and its gain of kinetic energy and consequent velocity is small. The best known instrument for this purpose is Atwood's Machine. It consists essentially of a light fixed pulley so mounted as to turn on its axis with very little fric-

tion, and a vertical scale on which the distances fallen by the body in successive intervals of time can be measured. A long thread with equal weights attached to its ends is placed over the pulley, and a small additional weight in the form of a light rider is placed upon one of the weights. The excess of potential energy on the side of the rider sets in motion both weights and the pulley, but since only the potential energy of the rider is employed in moving the whole system, the motion is much slower than in a freely falling body, and by choosing a light enough rider the motion can be made as slow as desired.

Experiments with Atwood's Machine.*

LABORATORY EXERCISE 17.—Place a light rider of known weight on the suspended weight of the Atwood's Machine which hangs in front of the scale. Taking hold of the cord on the other side of the pulley, draw it down until the bottom of the rider is exactly even with the zero at the top of the scale. Start the metronome or seconds pendulum, and release the cord exactly upon one of the ticks. Move the ring which serves to catch the rider into such a position that it will stop the rider exactly upon the next tick after the cord is released. To do this, adjust the height of the ring so that the tick of the pendulum and the click of the rider upon the ring will be heard exactly together. (The weight and rider should not fall more than eight or ten centimeters in the first second.)

To find the space passed through by the weight in the first second after the rider is removed, adjust the movable shelf so that the click of the weight upon it will be heard exactly with the second tick of the pendulum. Notice that the distance from the ring to the shelf must be decreased by the height of the weight to give the distance fallen in one second.

Adjust the shelf so that it will stop the weight at the end of the second, third, and following seconds of its fall. Does

* If desired by the teacher, these experiments may be performed on the inclined plane. The necessary modifications are easily made.

the weight fall with uniform velocity after the rider is removed?

How does the velocity acquired by the weight and rider in one second compare with their mean velocity during that second?

If the weight and rider had fallen 20 centimeters in one second, how far would the weight have fallen in one second after the rider was removed?

Repeat your experiments, leaving the rider on the weight for two seconds of its fall. How does the velocity which the weight and rider acquire in two seconds compare with the velocity which they acquire in one second?

Find the velocity acquired by the weight and rider in three seconds.

Letting t = time of fall with rider, v = velocity acquired, and S = space passed through by weight and rider in time t, tabulate your results in the following form. Complete the table for as many seconds as the height of the machine will permit.

t	v	S
1		
2		
3		
4		

Repeat the preceding experiments with another rider twice as heavy as the first.

In your experiments with Atwood's Machine you have found the weight and rider to fall with an increasing velocity. When the velocity of a moving body is increasing or decreasing, the body is said to have accelerated motion.

ACCELERATION

Definition of Acceleration.—The rate of change of velocity of a body, or, what is the same thing, the change of velocity in the unit of time, is called Acceleration.

Uniform Acceleration.—When the change of velocity in each unit of time is the same, the acceleration is said to be uniform.

Positive and Negative Acceleration.—When the velocity is increasing, the acceleration is said to be positive; when the velocity is decreasing, the acceleration is called negative.

Acceleration of Falling Bodies.—Referring to the tabulated results of your experiments, answer the following questions:

(1) What was the acceleration of the weights and rider first used during the first second of fall?

(2) Was the acceleration uniform as long as the rider remained on the weight?

(3) Did the weights have an acceleration after the rider was removed?

(4) Did the accelerations produced by the two riders bear any relation to the weights of the riders?

(5) How did the velocity acquired by the weights and rider vary with the time of fall?

(6) Using t, v, and S with the same significance as before, and letting a represent the acceleration of the weights and rider in the first second, give an expression for v in terms of a and t.

(7) Give an expression for S in terms of a and t. In terms of a and v.

Magnitude of the Gravitation Acceleration.—We have seen that the effect of gravitation upon an unsupported body is to give it a uniform acceleration toward the earth. The amount of this acceleration on a freely falling body cannot be accurately determined by the Atwood's Machine, since the falling body is constantly giving off energy to other parts of the machine. Careful experiments have shown that in the latitude of the United States the acceleration of gravity on a freely falling body not sensibly retarded by the air is about 32.16 feet or 980 centimeters a second.

Since the space passed through by a falling body in one second is numerically equal to half the acceleration

acquired in the same time, a body not retarded by the air will fall 16.08 feet or 490 centimeters in one second.

PROBLEMS.—The symbol generally used for the acceleration of gravity is g. Substituting the above numerical value of g for a in your Atwood's Machine equations, what velocity will a freely falling body acquire in five seconds? How far will it fall in five seconds? How far in the fifth second?

Since a body projected vertically upward loses velocity as fast as a falling body acquires it, with what velocity must a body be projected upward in order to rise for two seconds?

Since a falling body loses potential energy and gains kinetic energy at the same rate, its gain of kinetic energy must be proportional to the space through which it falls. Thus a pound mass in falling ten feet must acquire ten foot-pounds of kinetic energy. Calling the value of g 32 feet, how much kinetic energy will a pound mass gain in falling for one second? For two seconds? For three seconds?

How does the kinetic energy of a falling body vary with the time of fall?

A body projected upward with velocity V rises to height H; with what velocity must it be projected upward to rise to height $4H$?

A body with velocity V has kinetic energy E; what is its kinetic energy when its velocity is $2V$? When its velocity is $3V$?

A body having a mass of four pounds has a velocity of 96 feet a second; how many foot-pounds of kinetic energy has it? (To what height could this velocity carry it?)

UNIVERSALITY OF GRAVITATION

Gravitation Acceleration of the Moon. — It was shown by Newton that the motion of the moon around the earth indicates that the moon has an acceleration toward the earth of about .1 inch per second.* In order for this acceleration to be due to gravitation, the acceleration of gravitation for bodies above the earth's surface must decrease as the squares of their distances

* For demonstration, see foot-note, page 37; also page 55.

from the center of the earth increase. Thus the moon is sixty times as far from the center of the earth as a body on the earth's surface, while its acceleration toward the earth is $\frac{1}{3600}$ as great as that of bodies on the surface of the earth.

Gravitation Accelerations of the Planets and Satellites.—Newton also found that the movements of the satellites of Jupiter about their planet showed accelerations toward Jupiter decreasing as the squares of their distances from the planet increase, hence he concluded that gravitation acts upon Jupiter as upon the earth. But the earth and other planets of the Solar System have accelerations toward the sun varying inversely as the squares of their distances from the sun, so gravitation apparently acts throughout the Solar System. There are also many very distant double stars which revolve around each other, hence which have accelerations toward each other. The distances between these stars cannot be measured, but since they are known to be made of the same substances as are the bodies of the Solar System,* their accelerations are probably due to gravitation.

Since Newton was the first to discover the apparent universality of gravitation, his statement of the theory has come to be known as Newton's Law of Gravitation.

Newton's Law of Gravitation.—*Every particle of matter in the universe is attracted directly toward every other particle with a force varying directly as the mass of each particle, and inversely as the square of the distance between them.*

From what experiment have we previously concluded that gravitation varies as the mass?

* See paragraph on Absorption Spectra of the Stars.

FORCE

Definition of Force.—The physicists of the time of Newton had no notion of energy as one of the constants of the physical universe, and, following the mechanics of Galileo, they assumed that when an acceleration takes place in some part of a material system * it is due to a "force" exerted by some other part of the system. Newton accordingly speaks of gravitation as a force, and he regarded the weight of a body as a measure of the attractive force exerted upon it by the earth. Newton defined force as follows: "*Impressed force is action exercised on a body so as to change its state of rest or of uniform motion in a straight line.*" This assumes that a body at rest will remain at rest or a body in motion will continue to move uniformly in a straight line unless acted upon by a force. Expressed in the language which we have been using, *A force is whatever produces an acceleration.*

Measurement of Force.—Newton states that in his day the term force was measured in various ways, that is, that there was no general agreement as to how a force should be measured. He accordingly suggested a definition for the measure of a force which has been generally used since his time. His definition of force and his notion as to what should be regarded as the measure of a force are contained in his three laws of motion.

* By a material system is meant that part of the material universe which is, for the time being, the subject of investigation. It may be a single material particle, a body or number of bodies, or it may include the whole material universe.

Newton's Laws of Motion.

LAW I. Every body perseveres in its state of rest or of uniform motion in a straight line unless it is compelled to change that state by impressed forces.

LAW II. Change of motion is proportional to the impressed force and takes place in the direction in which the force is impressed.

LAW III. To every action there is always an opposite and equal reaction, or the mutual actions of two bodies are always equal and opposite.

It will be seen that the first law merely includes the definition of a force, i.e., "action exercised on a body so as to change its state of rest or of uniform motion in a straight line." Stated in the language of energy the first law would be: Every body perseveres in its state of rest or of uniform motion in a straight line unless it receives energy from or gives off energy to some other body. That is, every change in the velocity of a body is due to a change in its kinetic energy. A body moving with a uniform velocity in a straight line is neither gaining nor losing kinetic energy.*

* If it be true that a moving body not acted upon by a force will proceed in a straight line, then every example of motion in a curved line indicates the existence of a force. When this force ceases to act, the body will, according to the first law, proceed in a straight line in the direction in which it happened to be moving at the instant when the force disappeared. Thus the particles of mud thrown from a revolving wheel start off in straight lines tangent to the circumference of the wheel, instead of continuing to circle round the wheel. A stone thrown from a sling is another good illustration of the first law. The stone is held in the sling and is swung around the hand until it acquires a high velocity and is released at the instant when it is going in the desired direction. While the stone remained in the sling it was constrained by a force which prevented it from getting farther from the hand. To

In the second law, Newton defines his proposed measure of force. He says that the magnitude of the impressed force shall be regarded as proportional to the change of motion which it produces. Before we can measure the magnitude of a force we must accordingly have some way of measuring the quantity of motion of a given body, otherwise we cannot tell what change has been produced in this quantity of motion. Newton had previously defined quantity of motion as the product of the mass of the moving body into its velocity. That is, quantity of motion $= mv$.

Momentum.—The quantity represented by mv we now call Momentum. Hence the magnitude of a force is measured by the change of momentum which it will produce in a unit of time.

Since a force does not change the mass of a body, it can change its momentum only by changing its velocity,

compel a body to move in a circle, it must accordingly be acted upon by a force impelling it toward the center of the circle. .

Thus let a be a particle moving in a circle about the center c with a velocity which will carry it to b in one second. At the instant when the particle is at a it is moving at right angles to the radius ac, that is, in the direction ad. If it has at the same time an acceleration toward c which will carry it to e in the time that its velocity in a straight line will carry it to d, it will reach b in the same time that it would otherwise have required to reach d.

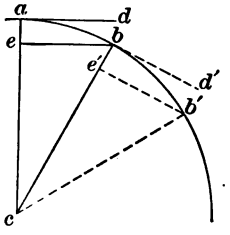


FIG. 11.

In the same manner, it will at the end of the next second reach b' instead of d'. Consequently a particle moving in the circle abb' with a velocity ab must have besides its uniform rectilinear velocity ad an acceleration toward the center of the circle which will carry it through the space ae in one second.

that is, by giving it an acceleration; hence a force is whatever produces acceleration.

The Force Equation.—Since change of momentum is proportional to change of velocity, that is, proportional to acceleration, a force which is measured by the change of momentum in a unit of time is measured by the mass times the acceleration which is given it by the force. The formula for force is accordingly $F = ma$.

Definition of Constant Force.—A constant force is one which produces the same change of momentum in each unit of time, that is, one which gives uniform acceleration. Is the weight of a body near the surface of the earth a constant force?

FORCE UNITS

The Poundal.—The unit of force in the English system of weights and measures is the poundal. It is defined as the force which would give to a mass of one pound an acceleration of one foot per second.

Since the gravitation acceleration is 32 feet per second, the force of gravitation on a pound mass is 32 poundals.

The Dyne.—The unit of force in the metric system is the Dyne. It is defined as the force which would give to a mass of one gram an acceleration of one centimeter per second.

Since the acceleration of gravitation is 980 centimeters a second, the weight of a gram in force units is 980 dynes.

The product of a mass in pounds into an acceleration in feet per second gives a force in poundals.

The product of a mass in grams into an acceleration in centimeters per second gives a force in dynes.

PROBLEMS.—Upon what mass is the force of gravitation equal to one poundal?

A force of one poundal acts for one second upon a mass of one ounce avoirdupois; what velocity does it give to it?

How far will a gram mass fall in one second under an attraction of one dyne?

ACTION AND REACTION

Definition of Action and Reaction.—In his third law Newton says that the mutual actions of two bodies are always equal and opposite. In order to understand his meaning in this statement, we must know what he means by "action." This we may make out from his use of the term in other places. In defining force he says, "Force is action exercised on a body," etc. But we have seen that force as a quantity is measured by the change in momentum which it produces in a unit of time, hence the "action" spoken of in the third law must be measured by the change of momentum which it produces. Used in this sense, the third law states that when two bodies act upon each other so that one body gains momentum in a given direction, the other loses an equal quantity of momentum in the same direction or gains the same quantity of momentum in the opposite direction.

The fact that there is often such a mutual gain of momentum in opposite directions is so well known as to need no experimental proof. The recoil of a gun when it is fired, the rotary motion of the common lawn-sprinkler, the backward motion given to a boat when one jumps from it, are good examples.

Equality of Action and Reaction.—The *equality* of momentum in action and reaction can be proved experimentally in many cases, while in others it can only be inferred. This equality in the case of a falling body assumes that the earth acquires as much momentum toward the body as the body acquires toward the earth. On account of the great mass of the earth, its acceleration toward a falling body is ordinarily inappreciable, but in the case of the moon's attraction it appears in the form of the tidal waves.

In the case of a man sitting in a boat and holding one end of a rope while another man walks on the shore and tows the boat by the rope, we see at first an apparent exception to the law. It is easy to see that both men must pull equally upon the rope, that is, if between each man's hand and the rope there was a spring balance these balances would indicate equal pulls; but if we consider only the men and the boat, the momentum seems to be all in one direction. When we consider the fact that the man who has been walking has pushed backward upon the earth as much as he has pulled forward upon the boat, we can see that when we take into consideration all the bodies concerned the momentums in opposite directions may still be equal. This would be seen at once if the man who tows the boat were walking along the deck of a larger boat while pulling. The two boats would then move toward each other with velocities (neglecting the friction of the water) inversely proportional to their masses.

Restatement of Newton's Third Law.—The third law of motion may accordingly be stated as follows: No mutual action between the parts of a material

system can change the momentum of the system as a whole; or, No mutual action between the parts of a material system can give motion to the center of gravity of the system. This is equivalent to applying the first law to systems made up of several bodies. Thus, *Every system of material bodies perseveres in its state of rest or of uniform motion in a straight line unless it is compelled to change that state by forces impressed from without the system.*

Direction of Momentum.—In his second law Newton says: "Change of motion is proportional to the impressed force and *takes place in the direction in which the force is impressed.*" Hence in describing a momentum it is always necessary to give its direction. When momentum in a given direction is called positive, momentum in the opposite direction must be called negative, otherwise the third law of motion will not apply.

Momentum of Rebounding Ball.—Thus a ball is thrown perpendicularly against a wall and rebounds with the same velocity with which it struck the wall. Its momentum before striking was mv toward the wall; its momentum after the rebound is mv in the opposite direction, or $-mv$. In order that the third law of motion may apply, we must assume that it has given to the wall the momentum $+mv$, and has taken from the wall the momentum $-mv$, which is equivalent to giving to the wall altogether a momentum $+2mv$.

Persistence of Momentum in Elastic Impact.

LABORATORY EXERCISE 18.—Two "collision balls"* of equal mass are suspended so as to form pendulums of the same length and so that when at rest their surfaces just touch each other. They are best made by suspending each ball

*The best collision balls are usually made of ivory. Steel balls are quite as good, and may usually be more easily obtained.

from two threads or fine wires separated at the top, so that the balls can swing in only one plane, and this should be the vertical plane in which both balls rest when in equilibrium. A scale placed to one side of the balls is convenient.

Draw one ball a measured distance to one side and let it swing against the other ball. Does the second ball gain as much momentum as the first ball loses?

Separate the balls by pulling both aside to equal distances and allow them to swing together. Calling momentum in one direction + and in the other direction —, the algebraic sum of the momentums at the instant of impact is zero; does it remain zero?

Replace one of the balls by a smaller one, making the two pendulums of the same length and suspending them so that they will touch as before. They will now swing in the same time, and as the time of vibration of each is nearly independent of its arc, the velocities with which they reach the centers of their arcs will be proportional to the distances through which they swing. If their masses are known, their relative momentums can be calculated by multiplying their masses by the distances through which they swing before reaching the centers of their arcs.

Pull the heavy ball to one side and let it swing against the lighter one, and determine if it loses as much momentum as the lighter one gains.

Let the lighter ball swing against the heavy one. Before striking, it had a certain positive momentum. After striking, it rebounds, and accordingly has negative momentum. Is the momentum acquired by the larger ball the algebraic sum of the momentum received from and the momentum given off to the smaller ball?

Does the smaller ball give to the larger one more momentum than it itself had before impact?

FORCE AND WORK

Force One Factor in Work.—We have seen that a force is measured by the formula $F = ma$, and that a force in poundals is measured by the mass in pounds times the acceleration in feet per second. Our unit of

work in the corresponding system is the foot-pound, and we have seen that it is the work done in raising a pound mass one foot against gravitation. But the force of gravitation on a pound is 32 poundals, hence to overcome a force of 32 poundals through one foot requires the expenditure of one foot-pound of energy.

In considering the relation of force and work there are accordingly two factors to be considered, the force, and the distance through which it is said to act or through which it resists action.

Equation for Force and Work.—Letting W stand for work, we have seen that F (in poundals) $\times$ S (in feet) $= \frac{W}{32}$ (in foot-pounds), or $32FS = W$.

The Erg.—The unit of work in the C.G.S.* system is the Erg. It is the work done in moving a body one centimeter against a force of one dyne.

Since the weight of a gram is 980 dynes, 980 ergs of work must be done in raising one gram through a height of one centimeter. Almost one erg of work is done in raising a milligram through one centimeter.

Since a mass of one gram will acquire a velocity of one centimeter a second from a force of one dyne, it will move only $\frac{1}{2}$ centimeter in that time, consequently a dyne acting for a second on a gram will do $\frac{1}{2}$ erg of work.

*Since the system of units based upon the centimeter, gram, and second (called the C.G.S. system) is used in most scientific works, the student should, as soon as possible, become familiar with the metric system of weights and measures. This can best be done by weighing and measuring bodies with metric units. Comparisons should be made with the corresponding units in the two systems. This is necessary work, but it is not Physics, and should be done when needed as a preparation for the work of Physics.

PROBLEMS ON FORCE AND WORK.—What acceleration will a dyne give to two grams in one second? How far will the two grams move in the second? How much work will a dyne do upon two grams in a second?

How far will a gram move in two seconds under the force of a dyne? How much energy will it acquire?

Tabulate velocity and kinetic energy of a gram under the force of a dyne for four seconds, as follows:

t	v	E
1	1	$\frac{1}{2}$
2		
3		
4		

Show that when the mass is measured in grams and the velocity in centimeters a second, the kinetic energy in ergs can be calculated from the equation $E = \frac{mv^2}{2}$.

The acceleration of gravity is 980 centimeters a second, what kinetic energy would a gram acquire in falling freely for one second?

A mass of 5 grams has an acceleration of 20 centimeters a second. What force is acting upon it? What kinetic energy will it acquire in 4 seconds?

A mass of 5 grams is acted upon by a force of 20 dynes; what kinetic energy will it acquire in 4 seconds?

Show that where the mass is measured in pounds and the velocity in feet per second, the kinetic energy in foot-pounds is given by the equation $E = \frac{mv^2}{2g}$.

What kinetic energy will a five-pound mass acquire in falling freely for four seconds?

Why must the equation $E = \frac{mv^2}{2}$ which applies to the units of the C.G.S. system be divided by g to give the kinetic energy in the foot-pound system?

Show that the potential energy of a body raised above the earth is expressed in the C.G.S. system by mgh, where h is the height in centimeters to which the body is raised.

Give the corresponding expression for the potential energy of a body in foot-pounds.

Potential.—It is customary, especially in the calculation of electrical energy, to speak of the "Potential"

of a point in space, meaning the potential energy which a unit quantity of electrification or a unit mass in grams would have if located at that point. The Gravitation-potential in ergs of a point above the earth is the number which tells how many ergs of potential energy a gram mass would have if raised to that point.

The symbol V is generally used to indicate a potential. In the case of the gravitation-potential, $V = gh$, where V is expressed in ergs. The potential energy of a body raised above the earth is accordingly $E = mV = mgh$.

The potential in foot-pounds of a point above the earth is $V = h$, where h is expressed in feet.

What is the potential in ergs of a point 5 meters above the earth?

GENERAL EQUATIONS OF MECHANICS

The relations which we have been considering between velocity, acceleration, force, momentum, and work, and the units of mass, time, and space as expressed in the C.G.S. system may be shown in the following equations:

$$\textit{Force} = F = ma = \frac{M}{t} = \frac{W}{S};$$

$$\textit{Velocity} = v = at = \frac{Ft}{m};$$

$$\textit{Acceleration} = a = \frac{v}{t} = \frac{F}{m};$$

$$\textit{Distance} = S = \frac{vt}{2} = \frac{at^2}{2};$$

$$\textit{Momentum} = M = mv = Ft;$$

$$\textit{Work} = W = E = FS = \frac{mv^2}{2} = \frac{Mv}{2}.$$

In general, when three of these quantities are known all the others may be calculated from them.

PROBLEMS.—Using the units of the C.G.S. system, fill in the blanks in the following table:

m	t	S	v	a	F	M	$W = E$
10	20	1000					
10	5		25				
	4		40		100		
10	5			8			
10	5				60		
1000	20				100		
.01	20				100		
		100				2000	20000
		180		10			9000
	20				5	100	
	12			10		1200	

COMPOSITION AND RESOLUTION OF MOTIONS AND FORCES

Composition of Motions.

LABORATORY EXERCISE 19.—We have seen that a body projected upward has a negative acceleration equal to the positive acceleration which it would have if allowed to fall freely toward the earth, hence we conclude that gravitation must act upon a moving body with the same force as upon a body at rest. A body projected horizontally should, accordingly, fall to the earth in the same time as one starting from a state of rest at the same height. To test this assumption, perform the following experiment.

Two coins are laid upon a table, one just balanced on the edge, as at A, and the other at a distance of a foot or more

from the edge, as at *B*. A ruler or meter stick is placed upon the table in the position *CD*, and is swung rapidly around *C* as a pivot, keeping it in contact with coin *B* until it reaches the edge of the table. In this way, *B* will be projected from the table with a considerable horizontal

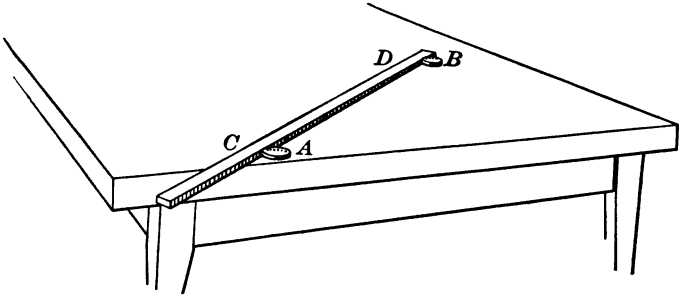


FIG. 12.

velocity, while *A* will fall directly to the floor. Do they both reach the floor at the same time?

Resultant Motion.—The motion of the coin which was projected farthest from the table may be said to be a "resultant" of two motions, the one the horizontal motion in a straight line given to the coin by the ruler, and the other the downward accelerated motion due to gravitation. If gravitation had not acted upon the coin, then, according to the first law of motion, it would have continued to move uniformly in a straight line. If it had received no horizontal impulse at the start, it would have fallen with an accelerated motion directly to the floor. The path which it does take is neither the one nor the other of the two mentioned, but is a curved line resulting from the two. That is, it moves with the same uniform horizontal velocity as it would if not acted upon by gravitation, and it falls to the floor in the same time as it would if it had no horizontal velocity.

Graphical Composition of Motions. — To trace graphically the path of a freely falling body having a horizontal velocity we may proceed as follows: Suppose a body to be thrown horizontally from the top of a tower 144 feet high with a velocity of 16 feet a

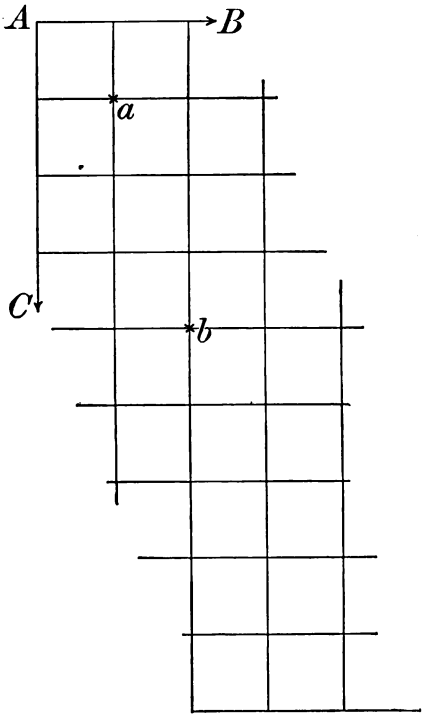


FIG. 13.

second. From the laws of falling bodies and the value of g we know that it will reach the earth at the end of three seconds, and from the first law of motion we know that in three seconds it will have travelled a hori-

zontal distance of 48 feet. We may then know, without knowing the path of the body, the place where it will strike the earth. To project the path of the body we rule a sheet of paper in convenient squares by means of vertical and horizontal lines, and let the side of one of these squares represent 16 feet (see Fig. 13). Then we suppose the body to be thrown from *A* toward *B* while it falls from *A* toward *C*. During the first second it will travel 16 feet in each direction, and at the end of the second it will be at *a*. During the next second it will move the same distance in a horizontal direction, but will fall through three times the vertical distance fallen in the first second. It will accordingly reach *b* at the end of the second.

Locate its position at the end of the third second. Draw a line from *A* to the final position, indicating the path followed by the body for three seconds.

Indicate in the same manner the path of a body thrown horizontally from *A* with a velocity of 24 feet a second.

We have seen that the resultant of a uniform velocity and an acceleration at right angles to each other is an accelerated motion in a curved path. By the same method of squares find the resultant of two uniform velocities at right angles to each other. Show that this resultant velocity is represented by the diagonal of the rectangle whose sides are proportional to the two constituent velocities.

The Parallelogram Law.—If a particle at *a*, Fig. 14, have two simultaneous velocities in the directions of and respectively proportional to *ab* and *ac*, then the position of the particle at the end of one second will be the same as if *ab* had acted for one second carrying it to *b*, and a velocity *bd*, parallel and equal to *ac*, had acted upon it for the following second, thus carrying it to *d*. If the two velocities act simultaneously, its path will accordingly be the straight line *ad*, represent-

ing the diagonal of the parallelogram of which *ab* and *ac* are two adjacent sides.

We may accordingly state the following law for the

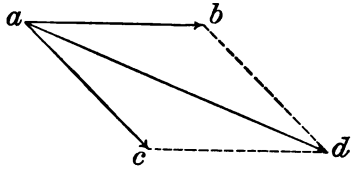


FIG. 14.

composition of two simultaneous velocities given to the same particle:

If a particle possess at the same time two velocities, and if these velocities be represented by lines drawn from the same point and forming two adjacent sides of a parallelogram, the resultant velocity will be represented by that diagonal of the parallelogram which is drawn from the point of intersection of the two lines.

The Triangle Law.—*If two velocities be represented by two sides of a triangle taken in order, their resultant may be represented by the third side.* This law follows at once from the argument used in developing the parallelogram law. It will also be seen from the figure that it is immaterial whether the two velocities are represented by *ab* and *bd*, or by *ac* and *cd*, the resultant being in both cases represented by *ad*.

Composition of More than Two Velocities.—To find the resultant of more than two velocities acting at the same time on a given particle, find the resultant of any two velocities, then of this resultant and a third velocity, and continue in this manner until all the velocities have been used. The last resultant will be the one sought.

Composition of Forces.

LABORATORY EXERCISE 20. — Two spring balances are attached by their hooks to the ends of a strong cord 50 or 60 centimeters long. The rings of the balances are tied by pieces of cord to two nails or pegs driven into a convenient board or a table at a distance apart about equal to the length of the string connecting the balance hooks. A third balance is attached in the same way to a cord about half as long as the one connecting the two other balances, and the end of this cord is provided with a loop which is slipped over the longer cord. When the cords are pulled straight, the balances should lie in a position similar to that shown in the figure.*

By means of a cord tied to the ring of the third balance, draw it out until it indicates a conveniently large reading, and tie it to another nail or peg. Tap the balances and cords until the loop has taken its position of equilibrium and the pointers indicate the true pull upon each balance. Place a sheet of paper with its center under the intersection of the cords, and indicate the position of this point of intersection by a dot on the paper, then laying a ruler carefully alongside the cord, indicate very accurately by dotted lines the direction of each cord from the point of intersection.

Remove the paper, and draw in full the lines indicating the directions of the cords, and produce each by dotted lines on the other side of the intersection. Select some convenient scale of length, as inches or centimeters, to represent the pull on the balances (thus a distance of 10 centimeters may represent a pull of 10 ounces, and the like), and lay off on each line a distance representing the pull on the corresponding string. Complete the parallelograms on each pair of lines thus laid off.

Do the dotted lines previously drawn become diagonals of these parallelograms?

The resultant of each pair of forces must be always equal and opposite to the third force by which it is balanced; are these resultants represented by the diagonals of the parallelograms which you have drawn?

* The three balances used in these experiments may, if desired, be replaced by three suitable weights attached to cords and suspended over two fixed pulleys.

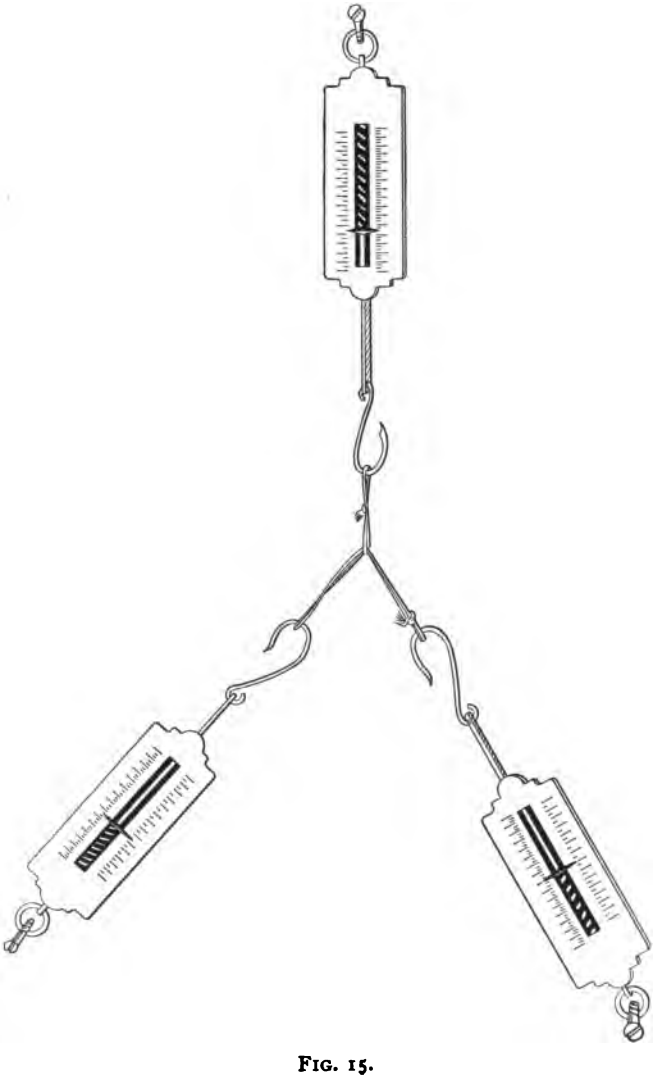


FIG. 15.

Repeat with the balance cords attached to different nails. Does the parallelogram law apply to forces as well as to velocities?

Resolution of Forces, Velocities, and Accelerations.—Any force or velocity or acceleration may be regarded as the resultant of two or more other forces, velocities, or accelerations. When the directions of these components are known, their magnitude may be calculated from the parallelogram law.

Thus, let *a* represent a sphere resting upon an inclined plane. The force acting upon the sphere is

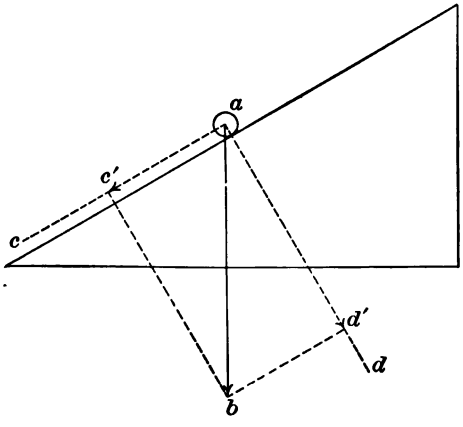


FIG. 16.

its weight, and the direction of this force is a vertical line. The sphere does not fall in a vertical line, but it rolls down the plane and at the same time presses upon the plane. The force by which it is impelled along the plane and the force of its pressure upon the plane are the two components of which the weight of the body may be considered the resultant. The direc-

tion of each of these forces is known. One is parallel to the plane, and the other, the pressure upon the plane, is perpendicular to the plane. The directions of these forces are then represented by the dotted lines *ac* and *ad*. If the direction and magnitude of the weight of the sphere be represented by the line *ab*, then is *ab* the diagonal of a parallelogram two of whose sides lie in the lines *ac* and *ad*. Completing this parallelogram, we find the magnitudes of the two component forces represented by *ac'* and *ad'*.

PROBLEMS.—Prove geometrically that the force *ac'*, which causes the motion of the sphere down the plane, is to the weight of the sphere as the height of the plane is to the length of the plane.

Referring to Exercise 6, on the inclined plane, by what was the force *ac'* represented?

A plank 10 feet long rests with one end on the ground and the other on a support 6 feet high. A barrel weighing 200 pounds is allowed to roll down the plank; what pressure does the plank support?

If the plank can support a pressure of 800 pounds, what load may be rolled down it?

The length of an inclined plane is to its height as 4 to 1. What velocity would a ball acquire in rolling freely down this plane for one second?

RESOLUTION OF CIRCULAR MOTION

Circular Motion a Resultant Motion.—We have already assumed (see foot-note on page 37) that motion in a circle can be resolved into a uniform rectilinear motion tangent to the circumference and an acceleration toward the center of the circle. Thus, if the particle *a* (Fig. 17) be moving with the velocity *ab* around *c* as a center, its motion along *ab* may be regarded as the resultant of the uniform motion *ad* and an acceleration which will carry it toward the center a

distance *ae* in one second. Since the space passed through in one second under the action of a constant force is numerically equal to one half the acceleration which measures the force, the acceleration of *a* toward *c* is equal to *2ae*.

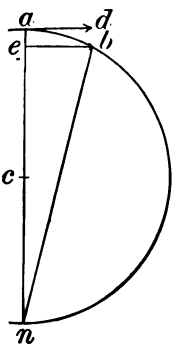


FIG. 17.

We know that *ae* is an acceleration, and not a uniform motion, because the resultant of two uniform rectilinear motions is also a uniform rectilinear motion.

We know that this acceleration is always toward the center of the circle and hence at right angles to the uniform rectilinear motion of the particle, as otherwise it could be resolved into two components one of which would be parallel to the uniform motion and would accordingly accelerate this motion and with it the motion of the particle in its circular path.

We now wish to find how this acceleration varies with the speed of the particle and with the radius of the circle.

If the arc *ab* be taken so small that it does not differ perceptibly from a straight line, then we know from geometry that the angle *abn* will be a right angle, and that we can make the proportion $ae : ab = ab : an$, and accordingly that $ae \times an = ab^2$.

Equation for the Acceleration Component.—Letting $a' = 2ae$ (the acceleration of the particle toward the center of its orbit), $v = ab$ (the orbital velocity of the particle) and $r = ac$ (the radius of the circular orbit), and substituting these values in the equation $ae \times an = ab^2$, we have $a'r = v^2$, and $a' = \frac{v^2}{r}$. Consequently

when a particle moves with uniform velocity in a circular path it has an acceleration toward the center of its orbit which varies directly as the square of the orbital velocity of the particle and inversely as the radius of the circle.

Centripetal Force.—The force which is assumed as the cause of the acceleration of the particle toward the center of its orbit is called the Centripetal Force of the particle. If the centripetal force ceases to act, the particle will at once leave its circular path and will continue with a uniform rectilinear velocity in the direction in which it was going when the centripetal force ceased. If the centripetal force be increased, its orbital velocity will be increased or its orbital radius diminished, or both. The centripetal force, like any other force, is measured by the formula $F = ma$, that is, by the mass of the moving particle times its acceleration toward the center of its orbit. Substituting for a its value as determined in the previous equation, we have $F = \frac{mv^2}{r}$, which is the equation for centripetal force.

Centrifugal Force.—The resistance which the moving particle offers to change of direction of motion is often called the Centrifugal Force of the body. Used in this sense, the centrifugal force is always equal in magnitude and opposite in direction to the centripetal force. This is, however, an incorrect use of the term force. A force is whatever produces or tends to produce an acceleration, and the particle has no acceleration or tendency to acceleration away from the center of its orbit. The particles of mud do not fly from a wheel because they are pulled off by a centrifugal force,

but because their attachment to the wheel is not strong enough to serve as the centripetal force necessary to their rapid circular motion. The stone in the sling does not pull upon the string because it has a force acting upon it to drive it away from the hand, but the hand, by means of the string, is constantly pulling it out of its rectilinear path.

Since the attraction between the particles of a liquid is not great enough to serve as a centripetal force in the case of rapid rotation, liquid particles are always thrown from the surface of a rapidly rotating body. This principle is often applied to the separation of liquids from solids. Thus in the centrifugal drying-machines used in laundries the wet clothes are placed in metal cylinders with perforated sides which are set in rapid rotation. The attraction between the particles of water in the cloth is not great enough to keep the water moving in the circular path, and it accordingly separates from the cloth and escapes through the perforations in the walls of the cylinder.

We have seen that the centripetal force increases as the mass of the rotating particle increases, hence when different liquids are mixed and set in rotation the heavier particles, which are held to the liquid mass by the same force as the lighter particles, sooner escape to the surface and gather on the walls of the containing vessel, while the lighter liquid is thus pressed toward the center of the rotating mass. This is seen in the hollow sphere containing mercury and water which is often attached to the rotating axis of a whirling table. When at rest, the mercury rests upon the bottom of the vessel and the water rests upon the mercury. When set in rotation, the mercury gathers in a liquid

band around the walls of the hollow sphere at the greatest possible distance from the axis of rotation.

This principle is often applied to the separation of a lighter liquid from a heavier, as in the centrifugal cream-separator. In this instrument the fresh milk is allowed to flow into a rapidly revolving vessel, the skim-milk separates from the cream and gathers on the outside, while the cream is pressed to the inside of the liquid mass, and each is drawn off into a suitable receptacle.

PROBLEMS IN CIRCULAR MOTION.—A stone in a sling is swung around the hand once a second, and the pull upon the string is 16 poundals. With what force must the string be pulled to cause the stone to swing around once in half a second? Once in two seconds?

A stone weighing two pounds is attached to a string two feet long and is swung around the hand once a second. With what force in poundals does it pull upon the string?

(*Solution:*

$$v = 2\pi r = 4\pi \text{ feet per second;}$$

$$a = \frac{v^2}{r} = 8\pi^2 \text{ feet per second.}$$

A poundal will give to one pound an acceleration of one foot per second, hence to give to 2 pounds an acceleration of $8\pi^2$ feet per second will require $16\pi^2 = 157.92$ poundals,

or $$F = \frac{mv^2}{r} = 16\pi^2 = 157.92.)$$

A mass of one kilogram on a radius of one meter makes one revolution per second; what is its centripetal force in dynes?

The rim of a fly wheel weighs 1000 pounds. Its radius is 5 feet. What centripetal force must be exerted by the spokes when the wheel makes 100 revolutions a minute?

PART II

PROPERTIES OF BODIES

STATES OF AGGREGATION

Three Kinds of Bodies.—Material bodies exist in three different conditions or states of aggregation, the Solid, Liquid, and Gaseous states.

ELASTICITY

Definition of Elasticity.—That property of material bodies which determines the state of aggregation in which a body shall exist at a given time is called Elasticity. Elasticity may be defined as that property of bodies by virtue of which they resist a change of form or a change of volume. The measure of elasticity is the measure of the force which is required to maintain a given change of form or change of volume in the body under consideration. Thus the elasticity of a bent spring is measured by the force which is required to hold it bent in a fixed position; the elasticity of a rubber band is measured by the force required to stretch it to a given length; the elasticity of the air in a bicycle tire or a football is measured by the pressure which it exerts upon the enclosing walls. Elasticity, quantitatively considered, is, accordingly, the resistance which a body offers to change of form or change of volume.

Perfect Elasticity.—Elastic bodies in which a given force is always required to maintain the same change of form or change of volume are said to have complete or perfect elasticity. Bodies which lose a part of their elasticity after being compressed or bent for a time are imperfectly elastic.

Rigidity.—The resistance which bodies offer to change of form is also called Rigidity, and a body which possesses rigidity is called a rigid body, or a solid.

Fluids.—Bodies which do not possess sufficient elasticity of form to enable them to retain their shape while supporting the pressure of their own weight are called Fluids. Such bodies spread out under the pressure of their own weight into thin layers, or take the shape of the containing vessel.

Two Classes of Fluids.—Fluids are divided into two classes, Liquids and Gases. Liquids have very little elasticity of form, but great elasticity of volume; that is, they offer great resistance to compression. Gases have no elasticity of form, and only relatively slight elasticity of volume.

Simplicity of Gaseous State.—Of these three states of aggregation, the gaseous state is much the simplest in its physical properties, hence we will consider it first.

GASEOUS STATE

PROPERTIES OF GASES

Indefinite Expansion.—A gaseous body, if not acted upon by any restraining pressure, will expand indefinitely, hence gases always occupy the entire volume of

the containing vessel and exert pressure upon its walls. This pressure is the measure of the elasticity of volume of the gas. It increases with the amount of gas enclosed in the containing vessel. Thus when the tire of a bicycle is open to the air the gas contained in it exerts no more pressure upon its walls than does the air outside. It is possible, however, by means of the inflating pump to force enough air into the tube to exert a great pressure upon its walls, so that the tire remains distended under the weight of the rider.

The Air Pump.—The property of indefinite expansion of a gas is made use of in the construction of the

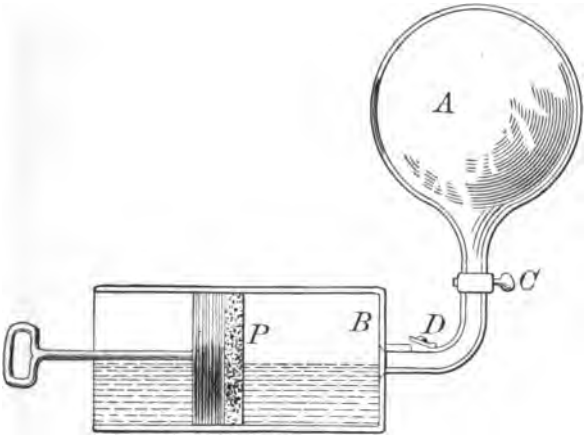


FIG. 18.

air pump. This instrument was invented by Otto von Guericke, of Magdeburg, about 1654, and in its original form is represented in the accompanying figure. *A* is the glass balloon or receiver from which the air is to be exhausted. *B* is a metal cylinder provided with

a tight-fitting piston, P; C is a stop-cock; and D is a valve opening outward.

To exhaust the air from A, the stop-cock C is closed, thus shutting off communication between A and B, and the piston is pressed down in the cylinder B. The valve at D is opened by the pressure of the compressed air, and part of the air escapes. The stop-cock C is then opened and the piston is withdrawn to the end of the cylinder. The air in A expands, filling both A and B. C is again closed and P is pushed inward, forcing another portion of the air out through D. This process is continued as long as the air inside the cylinder can be made to exert sufficient pressure to open D.

By means of this crude instrument von Guericke was able to perform many noted experiments on the pressure of gases. Later, the instrument was improved by

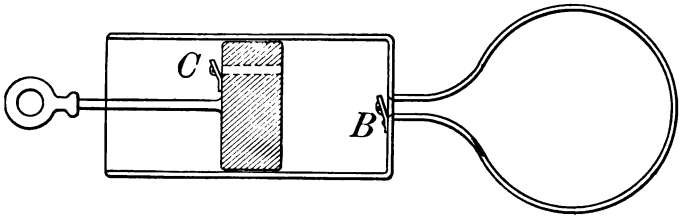


FIG. 19.

dispensing with the valve D and making C a three-way cock which could be turned so as to bring B in communication alternately with A and with the outside air. Then by placing C very near the cylinder nearly all the air on the side of C next to the cylinder could be forced out by the piston.

A common form of the air pump used at the present time is made by placing a valve B, opening toward the

cylinder, between the cylinder and receiver, and another valve, *C*, opening outward in the piston as shown in Fig. 19.

How would such a pump need to be modified to enable it to be used as a compression pump for inflating bicycle tires?

Explain the construction of a bicycle pump.

Weight of Air.

LABORATORY EXERCISE 21.—The weight of a known volume of air may be determined in the following manner:

A strong glass bottle holding a liter or more should be fitted air-tight with a one-hole rubber stopper, through which a short glass tube should pass into the bottle and project four or five centimeters beyond the stopper on the outside. To make the joints about the glass tube and the stopper air-tight, it may be necessary to pour melted beeswax or paraffin around them while the air is partly exhausted from the bottle so that the melted wax will be forced into any leaks by the pressure of the air on the outside. A piece of strong-walled but flexible rubber tubing should be placed over the glass tube, also making an air-tight joint, and this should project four or five centimeters beyond the glass tube and should be provided with a screw pinch-cock.

Place the bottle with the tube open and the pinch-cock upon one pan of the platform balance and carefully counterpoise it with shot or other heavy substances placed on the other pan. Then remove the bottle from the balance and attach the rubber tube to the air pump, slipping the rubber tube on so far that it will not collapse when the air is exhausted, and exhaust as much as possible of the air. Close the pinch-cock as near as possible to the glass tube, and remove from the air pump and place again on the balance with the counterpoise previously used. Add enough known weights to produce equilibrium. These weights represent the weight of the air which has been removed from the bottle.

To find the volume of air which was removed, squeeze the air out of the open end of the rubber tube and immerse the tube and the neck of the bottle in a large vessel of water and remove the pinch-cock. Do not let any air enter the bottle with the water. When the water has ceased flowing into the

bottle, lower it in the water until the water is at the same height inside and outside the bottle, then replace the pinch-cock and remove from the water. Pour the water out of the bottle into a graduated vessel and measure its volume. This will give you the volume of the exhausted air. Record the temperature of the air in the room at the time of your experiment.

PROBLEMS.—Calculate the weight of one cubic centimeter of air. Of one liter. Of one cubic meter.

Measure the dimensions of your laboratory in meters and calculate the weight of the air it contains.

Density of Air.—The density of a body in the C.G.S. system is its mass in grams per cubic centimeter.

What is the density of air from your determinations? What is it from the tables? What volume of air corresponds to the smallest weight indicated on your balance scale? Why should you use a large bottle in the preceding experiment?

Specific Gravity of Gases.—The Specific Gravity of a body is the ratio of its weight to the weight of an equal volume of some other body chosen as a standard, or, in other words, it is the ratio of the density of the body to the density of the standard body. The specific gravity of gases is generally determined with reference to air as a standard. Thus carbon dioxide is about 1.5 times as heavy as air, consequently its specific gravity referred to air is about 1.5.

To Find the Specific Gravity of Illuminating Gas.*

LABORATORY EXERCISE 22.—After carefully drying the bottle used in the preceding experiment place it upon the balance pan and counterpoise as before. Exhaust a part of the air and determine its weight as before.

Open a gas-cock for an instant to expel the air, and after

* Any gas contained in a receiver under a pressure slightly greater than the pressure of the air may be used in this experiment.

carefully squeezing the air out of the open end of the rubber tube on the bottle, slip this over the tube of the gas-cock. Turn on the gas and remove the pinch-cock from the rubber tube, thus filling the bottle with the gas. As the gas is forced in under a pressure slightly greater than that of the outside air, remove the rubber tube from the gas-cock for a moment before closing it with the pinch-cock. This will allow the gas on the inside of the bottle to come to the same pressure as the outside air. After closing the pinch-cock, return the bottle to the balance and weigh again.

Call the weight of the exhausted air w_1, and the weight necessary to produce equilibrium after the gas is in the bottle w_2. If the gas is heavier than air, w_2 will have to be added to the side of the counterpoise. Note that in this case the weight of the gas in the bottle is $w_1 + w_2$. If w_2 be added to the side of the bottle, it tells how much lighter the gas is than the exhausted air, hence the weight of the gas is $w_1 - w_2$.

Since the volume of the gas is the same as the volume of air which it replaces, the weight of the gas divided by the weight of the exhausted air is the specific gravity of the gas as compared with air. If the gas is heavier than air, its specific gravity is accordingly given by the equation sp. g. $= \frac{w_1 + w_2}{w_1}$; if lighter than air, by the equation sp. g. $= \frac{w_1 - w_2}{w_1}$.

What is the specific gravity of the gas from your experiment?

If the density of air be taken as .0012, what is the density of the gas?

The density of hydrogen is .0000895; what is its specific gravity referred to air of density .0012?

Pressure of the Atmosphere.—We have seen that air has weight, and that the air in an ordinary schoolroom weighs several hundred pounds. We know also that the air extends to a great height above us, and that consequently it must exert a great pressure upon all bodies with which it comes in contact.

To Show the Pressure of the Atmosphere.

LABORATORY EXERCISE 23.—Take an open glass tube bent as shown in Fig. 20, the short arm of which is about six inches long, and fill it with water to within about an inch

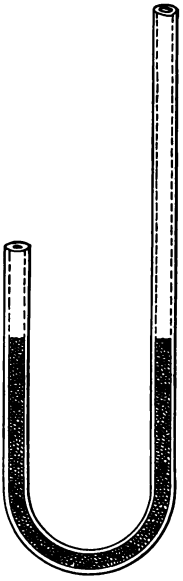


FIG. 20.

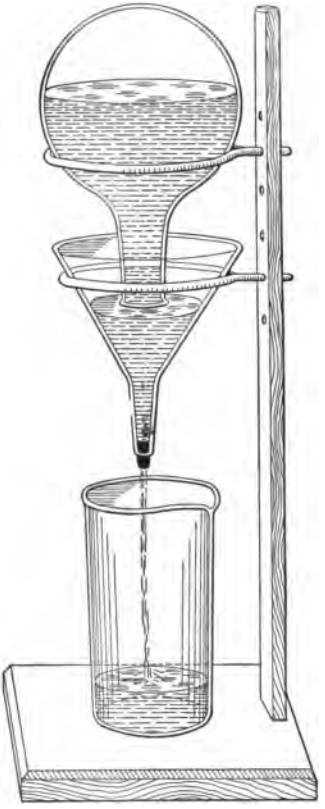


FIG. 21.

of the top of the short arm, then place the end of the long arm in the mouth and draw out part of the air. The water rises in the long arm. Now incline the tube until the water just comes to the top of the short arm, and holding the

thumb tightly on this end of the tube, again exhaust as much as possible of the air from the long arm. Does the water rise in the long arm as before? What conditions in the second experiment are different from the first? What apparently forced the air up the long tube in the first experiment?

Fill a bottle with water and invert it with its mouth below the surface of water in another vessel. What sustains the column of water in the inverted bottle? Raise it out of the water. Why does the water flow out?

Completely fill a drinking-glass with water, cover it with a stiff card in contact with the water and, holding the card in place with the hand, invert the glass and remove the hand. What holds the card against the glass? Slide the card to one side and allow a few bubbles of air to enter the glass. Why does the card fall?

Plug the stem of a funnel with a cork or piece of wood, leaving only a small hole for the escape of the liquid. Support the funnel on a ring, fill a large bottle or flask with water and invert it with its mouth in the funnel, as shown in Fig. 21. At first the water flows out of the bottle into the funnel faster than it can flow out of the funnel. Why does not the funnel overflow? At what level does the water come to rest in the funnel? Why? When does more water flow out of the bottle? Why?

The student-lamp is constructed on the principle used in this apparatus. Its purpose is to maintain a constant height of oil about the wick.

Measurement of Atmospheric Pressure.

LABORATORY EXERCISE 24.—A glass tube about one meter long and of about one centimeter internal diameter should be closed at one end by sealing off in a flame. Fill this tube completely with clean, dry mercury, and holding the thumb tightly over the open so as to exclude all air, invert the tube and place the open end beneath the surface of mercury in a convenient vessel and remove the thumb.*

* All experiments with mercury should be performed over a vessel arranged to catch any mercury that is spilled. A tin or brass vessel should not be used, but an iron baking pan is well adapted to the purpose.

Mercury should not be put in thin-walled glass vessels, and should not be allowed to come in contact with other metals than iron. To free

What supports the column of mercury in the tube? Why does it not stand to the top of the tube? Does raising or lowering the tube in the mercury vessel change the height of the column in the tube?

This experiment was first performed by Torricelli in 1643, and the inverted mercury tube came to be called Torricelli's Tube. The empty space at the top of the tube is called the Torricellian Vacuum.

Measure the height of the mercury column in the tube above the mercury in the vessel. What is this height in centimeters? In inches?

A cubic inch of mercury weighs approximately half a pound. If the bore of your tube had a cross-section of a square inch, what weight of mercury would be contained in the tube above the level of the mercury in the vessel? What would be the downward pressure of this mercury column upon a square inch of mercury in the vessel? What must be the atmospheric pressure upon a square inch of the mercury surface in the vessel?

A cubic centimeter of mercury weighs 13.6 grams. What is the atmospheric pressure in grams per square centimeter upon the surface of the mercury in the vessel?

What depth of mercury over the entire surface of the earth would exert a pressure upon the earth equal to the pressure of the atmosphere?

The Barometer.*—A Torricellian tube prepared as

it from grease and dirt, filter through pin-holes in stiff paper or squeeze through chamois-skin.

*The instructions generally given for preparing a barometer include the boiling of the mercury in the tube to expel all the air and moisture. This is a difficult operation in the ordinary laboratory. A good barometer may be made without this precaution by the following method:

The tube should be of tolerably thick-walled glass with a bore of at least half a centimeter in diameter. It should be carefully cleaned with water containing caustic potash or ammonia, then with water containing some nitric acid, and afterward with pure distilled water. It should then be carefully drained and dried by heating in a tube filled with sand or by warming the whole length of the tube evenly over a flame. The mercury should be clean, and should be dried by heating to 100° C., or more.

The tube should be placed upright while warm, and the hot mercury

in the preceding experiment and provided with a scale for measuring the height of the mercury column is called a Barometer, and is used for measuring the atmospheric pressure and for indicating any changes in this pressure. Since the atmospheric pressure at a given place changes with changes in the atmospheric conditions, the barometric height may serve as an indication of these changes.

Since the pressure due to the weight of the air must decrease as we ascend toward the top of the atmosphere, the barometric height must decrease as the barometer is carried to higher altitudes. This fact was first discovered by Pascal, and it is now extensively used in measuring the heights of mountains.

Two principal forms of the mercury barometer are used, the one used in our experiment, called the Cistern Barometer because the open end of the tube dips into a cistern of mercury, and the other, called the Siphon Barometer, in which the open end of the tube is bent upward like the letter J and is left open to the air. This form is shown in Fig. 22. The pressure of

should be poured in through a funnel until the tube is filled to within two or three centimeters of the top. It should then be closed with a clean cork and allowed to stand for several hours. Several small air bubbles will probably gather on the glass, and these must be removed by sweeping them out with a large air bubble. To accomplish this, hold the cork in place with the thumb and invert the tube slowly, allowing the air in the tube to flow in the form of a large bubble along the upper side of the tube, sweeping out the smaller bubbles. Repeat this process until all the visible bubbles have been removed, and allow the tube to stand for several hours again. If other bubbles appear, remove them as before. When free from air, fill the tube completely full of mercury, and hold a piece of clean sheet rubber tightly against the end with the thumb while inverting the tube in the cistern. Great care must be taken not to allow any air to enter while the tube is being inverted and opened.

the air upon the mercury in the open arm then supports the mercury column in the closed arm. Both forms were invented by Torricelli. The method of measuring the atmospheric pressure is the same in both forms.

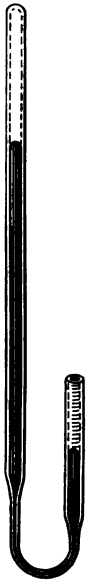


FIG. 22.

Since the volume and density of a gas vary with the pressure upon it, it is customary to give in the tables the volume or density under what is known as the standard atmospheric pressure. This standard pressure is taken as the pressure which will support a mercury column 30 inches or 76 centimeters high. By a pressure of one atmosphere we accordingly mean a pressure of 1033 grams per square centimeter or, in round numbers, 15 pounds to the square inch.

Since a soap bubble or a toy balloon retains the spherical form under this great pressure, the pressure must be equal in all directions. If the vertical pressure were greater than the horizontal, the bubble or balloon would be flattened on the top and bottom.

Since a soap bubble takes the spherical form while being blown, it must be that the pressure of the air which is forced into it is transmitted uniformly in all directions.

Atmospheric Pressure and Respiration. — The process of respiration in the animal body is largely carried on by means of the atmospheric pressure. The lungs are elastic bags suspended within a closed cavity whose dimensions can be changed by the contraction of muscles within its walls. The elastic walls of the

lungs themselves require but little pressure to stretch them (not more than a fourth of a pound to the square inch), consequently the pressure of the external air keeps them expanded, and causes them to entirely fill the pleural cavity in which they are suspended, and to press against its walls. When the pleural cavity is enlarged by the contraction of the external intercostal muscles and the muscles of the diaphragm, more air is pressed into the lungs, causing them to expand as the pleural cavity expands. When the internal intercostal muscles contract and the muscles of the diaphragm relax, the walls of the pleural cavity contract and compress the lungs, thus forcing some of the air out of them.

When we "suck the air out" of a vessel we merely make the pressure of our lungs upon the enclosed air less than the pressure of the air in the vessel, and this air expands under the lessened pressure and a part of it enters the lungs. We can accordingly suck only enough air out of a vessel to make the pressure of the air in it the same as the pressure of the air in our lungs.

In forced inspiration the chest expands enough to lower the pressure of the air within the lungs by about 150 grams to the square centimeter, and by a special effort enough air can be sucked out of a tube to cause the pressure of the outside air to raise a column of water two meters or more in the tube. That is, the pressure of the air within the lungs may be decreased by about $\frac{1}{8}$ of an atmosphere.

Pressure of Fluids Within the Body.—Since the atmosphere exerts a pressure of 15 pounds to the square inch upon all the external and internal surfaces of the body which open to the air, the fluids of the body must exert a like pressure upon the walls of their con-

taining vessels to prevent these walls from collapsing. If the external pressure upon any part of the body is removed, the internal pressure will distend the blood-vessels and other cavities containing the fluids toward the region of decreased pressure.

Experiment with Hand-glass.

LABORATORY EXERCISE 25.—Place a hand-glass on the plate of an air pump, hold the hand tightly on the top of the glass and exhaust some of the air from the glass. Note the feeling and appearance of the hand, and explain the cause.

PROBLEMS.—A barometer tube is filled with mercury and inverted in a mercury cistern, and the column of mercury stands 30 inches high in the tube. It is then pressed down into the cistern until the top of the tube is only 20 inches above the surface of the mercury in the cistern; what is the upward pressure per square inch of the mercury column against the top of the tube?

What, when the top of the tube is only 10 inches above the surface of mercury in the cistern?

Is the external pressure of the air upon the end of the tube greater or less than the internal pressure of mercury against it?

If the tube were made of thin rubber at the end, would it expand or collapse?

Two barometer tubes less than 30 inches long stand side by side with their tops at the same level, but the surface of the mercury in one cistern is 10 inches higher than in the other cistern; how much greater is the upward pressure of the mercury column in the shorter tube?

Two barometers stand side by side and are connected by three cross-tubes, provided with stop-cocks as shown in Fig. 23. The mercury stands 30 inches high in each tube, but the surface of mercury in cistern *B* is 10 inches higher than in cistern *A*.

Will the height of either column be affected by opening cock *a*, which is above the mercury in both tubes?

Cock *b* is 4 inches below the top of the column in *B*, but above the top of the column in *A*.

If *b* is opened, mercury will flow from *B* into *A*. What

pressure will be required to stop this flow? How long will the flow continue?

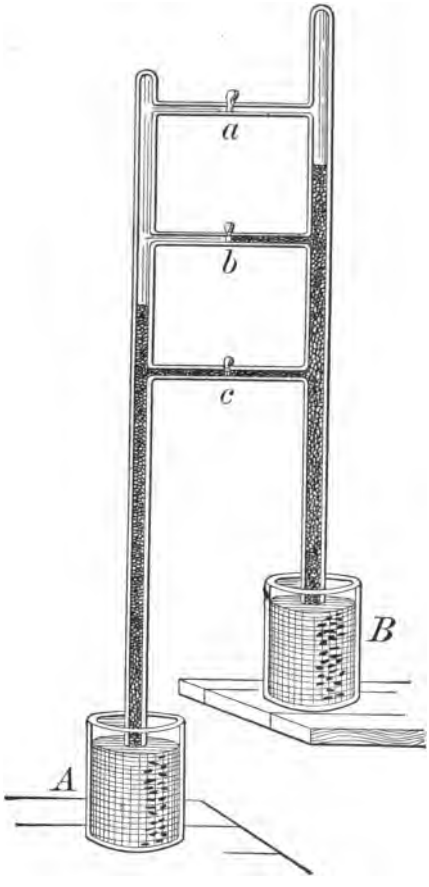


FIG. 23.

If *b* is closed and cock *c* is opened, what pressure will be required to stop the flow towards *A*? Would this pressure be the same, or different, if both tubes were sealed off just above the cross-tube *c*? When will the flow cease?

A U tube is filled with mercury and inverted with its ends in different vessels of mercury. It stands with the top of its bend 8 inches above the mercury in one vessel and 12 inches above the mercury in the other; will the mercury flow from

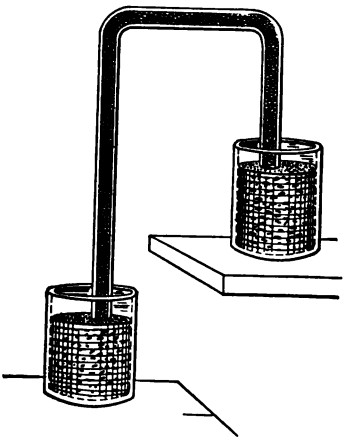


FIG. 24.

one vessel to the other? If so, what pressure will be required to stop its flow?

The Siphon.

LABORATORY EXERCISE 26.—Fill a U tube with water and, closing the ends, invert it with the ends in two vessels of water. Raise one vessel until the water is higher in it than in the other, and explain what occurs.

Such a tube is called a Siphon. It is often used to draw off liquids from one vessel into another.

Since the liquid is raised in the siphon, as in the barometer, by atmospheric pressure, the upward pressure against the bend of the siphon is the atmospheric pressure less the weight of the column of liquid supported. If this pressure is the same in both arms of the tube, no flow will take place. The pressure which causes the flow is the difference in the weight of the liquid column in the two tubes.

Can you raise water from a lower to a higher level by means of a siphon?

Over what height can mercury be made to flow in a siphon?

To what height can water be siphoned?

If a siphon tube were made of thin rubber, would it expand or collapse?

Pumps.—In the common suction pump used in raising water a piston provided with a valve opening upward moves air-tight in a cylinder at the bottom of which there is also a valve opening upward. When the piston is lowered, the piston valve is pressed open by the confined air, while the valve in the bottom of the cylinder is kept closed by the same pressure. The air accordingly passes through the piston valve above the piston. When the piston comes to rest, its valve closes by its own weight, and when the piston is raised it raises most of the air in the cylinder and relieves the lower valve of the downward pressure of the atmosphere. The atmospheric pressure upon the water outside the cylinder forces it up into the cylinder and through this valve. As the process is repeated, the air is all drawn out of the cylinder and the water rises to the piston. When the piston is then forced down, some of the water passes through the piston valve and is then raised by the piston and flows out through the spout.

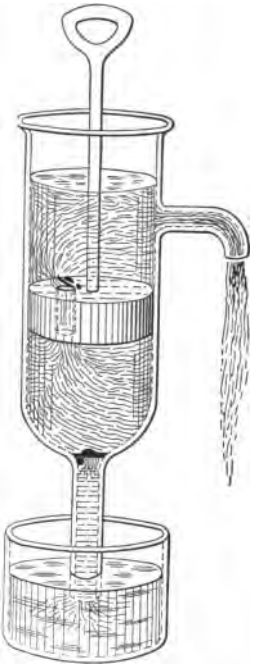


FIG. 25.

Could such a pump be made to work with the outflow spout below the piston?

When the barometer stands 30 inches high, what is the maximum height to which water can be raised by a suction-pump?

In the force pump the piston has no valve and the outflow pipe opens into the cylinder below the piston and has a valve opening outward. When the piston is forced downward the water is pressed into this side tube against the pressure of the atmosphere and the weight of the water already in the tube. The height

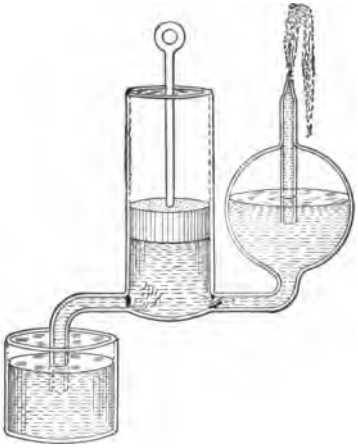


FIG. 26.

to which it can be thus forced depends only upon the pressure which can be applied to the piston.

In many pumps of this class the water is forced into an air chamber in which it compresses the air and then flows out through a discharge pipe. The compressed air serves to keep the discharge constant. Fire engines are pumps of this class.

LAWS OF GASES

Relation of Gaseous Volume to Pressure.—We have seen that a gas is compressed into a smaller volume by an increase of the pressure upon it, but we have not yet seen how much the volume is changed for a given change of pressure. This relation of volume to pressure was first discovered by Robert Boyle in 1662, and the method adopted by him is still used in making the same determination.

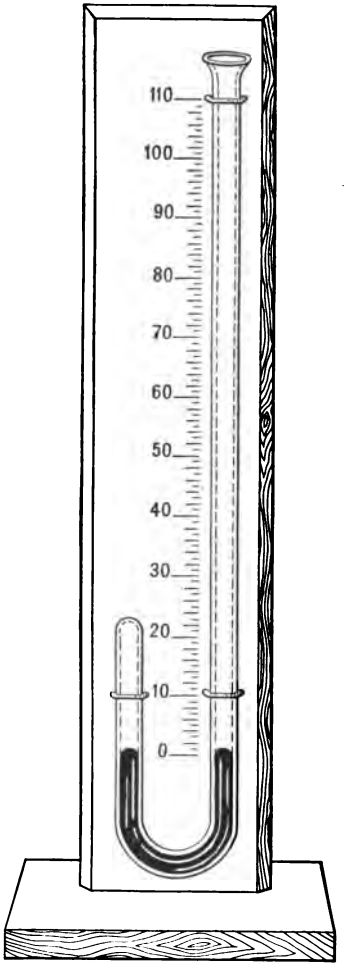


FIG. 27.

Boyle's Experiment.

LABORATORY EXERCISE 27. —The instrument used by Boyle for determining the relation between the volume and pressure of a gas, and known as Boyle's Tube, is a long J tube, the short arm of which is sealed and the long arm of which is about a meter in length. If this form of tube is used, pour enough mercury in the open arm to just fill the bend of the tube, as shown in the figure. By tilting the tube and allowing bubbles of air to pass from one tube to the other, the pressure of air in the closed tube can be regulated until the mercury stands at exactly the same height in both arms of

the tube. The air in the closed tube then presses upon the mercury as much as the air in the open tube. This pressure in centimeters or inches of mercury is measured by the height of the barometer column at the time of the experiment. If this cannot be read from the barometer, it may be taken as it was determined in Exercise 24. Measure the length of the air column in the closed tube as it stands under the pressure of an atmosphere. Call this length v_1, and the height of the barometer column p_1. Then pour mercury into the longer tube until it is about one third full. Measure again the length of the air column in the closed tube, calling this length v_2, and measure the height of the mercury in the open arm above the level of the mercury in the closed arm. This height represents the additional pressure upon the air in the closed tube. Add this height to the height of the barometer column to give the total pressure upon the enclosed air, and call this pressure p_2.

Fill the tube about two thirds full of mercury and determine the values of v_3 and p_3.

No.	v	p	$v \times p$
1			
2			
3			
4			

Now pour mercury into the open tube until the value of v_4 is one half v_1, and find the value of p_4.* Write your results in parallel columns and the products of p_1 and v_1, p_2 and v_2, etc., in a third column as indicated in the diagram.

Compare the results obtained in the last column.

Boyle's Law.

The law of the relation of volume to pressure in a gas, known as Boyle's Law, is generally stated as follows: "*The*

* An improved form of Boyle's Tube is now made by connecting an open and a closed glass tube by a long piece of strong rubber tubing, filling the rubber tube and about half the length of the glass tubes with mercury and mounting them side by side on an upright board so that either one can be clamped at any height on the board. To bring the air in the closed tube under atmospheric pressure, it is only necessary to make the height of the mercury column the same in the open and the closed tube. If this instrument is used, make measurements of the air column at less than atmospheric pressure, as well as under the increased pressures as directed above.

volume of a given mass of gas, kept at a given temperature, is inversely as the pressure."

Do your results show this for air?

Stated as an equation, this means, *The numerical product of the volume into the pressure of a given mass of gas is a constant;* or stated in algebraic symbols, $pv = c$.

This law holds very approximately for all gases when they are not compressed into too small a volume, and when they are not cooled to a temperature too near that at which they condense to liquids.

PROBLEMS.—What would be the length of the air column in your Boyle's Tube under a pressure of four atmospheres? Under a pressure of one-fourth atmosphere?

How could you measure the barometric height by means of a Boyle's Tube?

How does the density of a gas vary with the pressure which it sustains?

What is the density of air under a pressure of 10 atmospheres? Under a pressure of half an atmosphere?

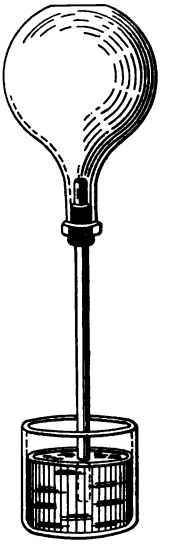


FIG. 28.

Relation of a Gas Volume to Temperature.—If a glass bulb provided with a stem of small bore, or a bottle with a glass tube of small bore passed tightly through its stopper, be inverted with the open end of the tube in a vessel of water and the bulb or bottle be warmed by the hand or otherwise, the enclosed air will expand and some of it will bubble up through the water. If the bulb be now cooled, the air in it will contract and the water will rise in the stem. The volume of a gas accordingly depends not only upon the pressure which it supports, but also upon its temperature.

Measurement of Heat Expansion of a Gas.

LABORATORY EXERCISE 28.—A glass tube about 50 centimeters long and with a bore of from 2 to 3 millimeters should be cleaned and dried and one end sealed off abruptly in a flame, keeping the bore uniform as near as possible to the closed end of the tube. Warm the tube throughout its length over a flame, until it is as hot as it can be held in the hand, and place its open end below the surface of mercury in a vessel and allow it to cool until a column of mercury 5 or 6 centimeters long has entered the tube; then place the tube upright with its closed end down, and by means of a fine iron wire lower the mercury column in the tube until the enclosed air column is 30 centimeters or more in length. This can be done by pushing the wire slowly through the mercury, when a bubble of air will rise along the wire and the mercury will sink for a small distance. If the mercury breaks up into separate parts, it can be brought together by drawing off by means of the wire the air between the parts. In a very few trials the mercury can be placed in any desired position.

Make a mark on the tube 273 millimeters* from the closed end, allowing for the contraction at the end of the tube, and stand the tube in a tall vessel filled with broken ice or snow so that the enclosed air will be entirely surrounded by the ice and water. After the air has had time to cool to the temperature of the ice, lower the bottom of the mercury index carefully to your mark and withdraw the tube from the ice and place it in a vessel of hot water, immersing it as before to the top of the air column. When the mercury has come to rest, measure the temperature of the hot water with a Centigrade thermometer, and measure the length of the column of enclosed air. The increase of volume will be proportional to the increase of length of the air column.

By what length does the air column expand for each degree of increase of temperature?

By what part of its zero volume does it expand for each degree of increase of temperature?

If its rate of expansion remains uniform, to what temperature must it be heated to double its zero volume?

* Any other length of air column can be used if its zero length is carefully determined.

If its volume continues to contract on cooling below zero at the same rate as above zero, at what temperature would its volume become zero?

The number by which the volume of a gas quantity taken at zero temperature must be multiplied to give its change of volume for one degree of temperature is called its coefficient of cubical expansion. Thus if v_0 represent the volume at zero and b represent its coefficient of cubical expansion, its volume at ten degrees is $v_{10} = v_0(1 + 10b)$; or in general, if v represent the volume before expansion and v' the volume after expansion, $v' = v(1 + bt)$, where t expresses the temperature change.

What is the coefficient of cubical expansion of air from your data?

Law of Charles.—The Law of Charles, sometimes called the Law of Gay-Lussac, states that *All gases expand or contract by 1/273 of their zero volume for a change of temperature of one degree Centigrade.*

The coefficient of cubical expansion of a gas is, therefore, 1/273.

To determine this expansion accurately, the expansion of the containing vessel must be taken into consideration.

How great is the error of your determination? What part of the whole coefficient is your error? What percentage of the whole coefficient is your error?

Absolute Temperature.—The instrument used by you in measuring the gas expansion may be regarded as a thermometer, because by means of it you may measure the temperature of a body or of the air. If the zero of temperature correspond with the zero of volume, and if the Centigrade zero be marked 273° on your tube, then the gas volume will vary as the temperature varies. That is, the length of your air column is 273 millimeters at a temperature of 273° on your

scale, and its length will be 373 millimeters at a temperature of 373°, and so following.

A gas thermometer so graduated that the volume of the gas will increase as the temperature increases and decrease as the temperature decreases is said to be graduated in the absolute temperature scale. It is known, however, that gases do not contract according to Charles' Law until their volume disappears. Before this temperature is reached, the gas will become a liquid, and its volume contraction will be much less. A gas thermometer cannot be used for measuring temperature near the zero of the absolute scale.

To change the reading of a Centigrade thermometer to the absolute scale, we add 273° to its readings.

Change of Pressure with Change of Temperature. —Gases expand according to the Law of Charles under any ordinary pressures, consequently to maintain the volume of a gas constant while it is being heated the pressure must be increased. By heating to 373° Centigrade its volume is doubled. To reduce it to its original volume, the pressure must be doubled. Accordingly the constant product pv which you determined with the Boyle's tube is only constant so long as the temperature is constant. Some of your variations from Boyle's Law were probably due to temperature changes in the enclosed gas during the experiment.

Since the product pv is a constant, and since if p remains constant v changes by $1/273$ of its zero value for every degree of temperature, it must be likewise true that if v be kept constant p must change by $1/273$ of its zero value for every degree of temperature.

The Gas Equation.—We may then combine the two statements and say that the product pv changes by

1/273 of its zero value for every Centigrade degree of temperature change, or, if we use the absolute scale of temperature instead of the Centigrade scale, we can say that pv varies as the absolute temperature, or algebraically $pv = cT$, where c is a constant factor and T is the absolute temperature of the gas.

When the barometer stands 76 centimeters high a quantity of gas in a Boyle's tube is warmed from 0° C. to 10° C. What height of mercury must be added to the long arm to restore the gas to its original volume?

The value of the constant c can be calculated for any given volume of a gas. We have previously seen that a gas volume must always be measured under a standard pressure of 76 centimeters or 30 inches of mercury, and we have now seen that the temperature must be specified if different gas volumes are to be comparable with each other. It is accordingly customary to specify the volume of a gas under standard pressure and standard temperature, and the temperature of melting ice, which is the Centigrade zero or the absolute 273°, is taken as the standard temperature.

PROBLEMS.—To calculate the value of the constant c for one liter of air under standard conditions of temperature and pressure we proceed as follows:

Our equation is

$$pv = cT, \quad \text{or} \quad c = \frac{pv}{T}.$$

p is 1033 grams and the weight of one gram is 980 dynes; hence

$$p = 1033 \times 980 \text{ dynes};$$
$$v = 1000 \text{ cubic centimeters};$$
$$T = 273°.$$

Hence

$$c = 1033 \times 980 \times 1000 \div 273 = ?$$

What volume of air at 20° C. and under standard pressure is equivalent to 1 liter under standard pressure and temperature?

A liter of air measured under standard conditions is again measured under a pressure of 57 centimeters and a temperature of 25° C. What volume does it occupy?

Calculate the value of the constant c in both cases.

Using the density of air as determined in Laboratory Exercise 21, find the value of the constant c for 2 grams of air under standard pressure at a temperature of 27° C.

Work Done by Expanding Gas.—We have seen that a volume of gas kept under constant pressure will expand 1/273 of its zero Centigrade volume for one degree increase of temperature. Since in expanding it must push back the outside air, it must accordingly do work. We have seen that work is measured by the product of the force into the distance, or $W = FS$. Here the force is the pressure in dynes of the outside air, the space is the distance through which this air is pressed back by the expanding gas.

PROBLEMS.—Suppose a horizontal glass tube with a bore of one square centimeter cross-section to contain at 0° C. a column of air 273 centimeters long which is separated from the outside air by a frictionless piston. Let this tube be warmed through 10° C. and calculate the work done by the expanding gas.

(The gas expands and pushes the index 10 centimeters along the tube. The pressure is 1033×980 dynes. The work is accordingly $1033 \times 980 \times 10$ ergs.)

Suppose the bore of the tube to be one half as great and the length of the air column to be twice as great as before, is the work the same? Is the change of volume of the gas the same?

Suppose the pressure upon the gas to be one half as great. Its initial volume will then be twice as great and its increase of volume due to heating will be twice as great. It will accordingly overcome one half the previous pressure through

twice the previous distance and will do the same quantity of work as before.

Suppose a gas under standard pressure in a cylinder whose cross-section is 10 square centimeters and let it expand by heating until its volume is increased by 10 cubic centimeters. How much work must it do?

If the volume of a gas before expansion is v_1, its volume after expansion is v_2, and the pressure in dynes under which it expands is p, the work in ergs done by the expanding gas is $W = (v_2 - v_1)p$. Show that this equation applies to the preceding problems.

State the above equation in words.

A liter of gas under standard pressure is heated from 0° C. to 273° C.; what quantity of work does it do in expanding?

Universality of Gas Equation.—In our experiments upon gases thus far we have used only air, and it would be rash to infer that the laws relating to the volume and pressure of air are true for all gases. Many thousand experiments made by a great many observers on different gases have shown, however, that in their physical properties all gases are very much alike. They may differ in density, in color, in chemical properties; but the gas laws of Boyle and Charles apply with only slight modifications to all gases not near their state of liquefaction.

Dalton's Law.—In 1801 John Dalton announced as the result of his experiments upon a number of mixed gases that "The total pressure of a mixture of gases equals the sum of the pressures of the individual gases." That is, if a closed vessel contain oxygen enough to exert a pressure of 5 pounds to the square inch and nitrogen enough to exert a pressure of 10 pounds to the square inch the total pressure upon the walls of the vessel will be 15 pounds to the square inch.

In other words, a gas exerts the same pressure upon the walls of the containing vessel whether it occupies the space alone or with another gas.

NATURE OF GASES

All Gases have Similar Structure.—The remarkable similarity in the physical properties of gases has led to the belief that in their structure all gases must be very much alike. This is not true in the same sense of liquids and solids. Scarcely two of these can be found which have the same expansion coefficient or which are affected by the same amount for a given change of pressure. They are accordingly supposed to be much more complex in their internal structure than are gases, and we regard the gaseous state of aggregation as the simplest condition in which bodies are known to exist.

Two Possible Theories of Gas Structure.—There are two possible assumptions, and apparently only two, concerning the structure of gases. One is that a gas is a continuous substance of small density which expands indefinitely and fills all the space at its disposal; and the other is that a gas is made up of disconnected particles which separate as far as possible from each other, and hence occupy all the space at their disposal.

Comparison of Two Theories. — Under the first assumption, when several gases fill the same vessel their substances actually interpenetrate each other so that any material point taken in the vessel will be at the same time a part of all the gases. Under the second assumption, no two gas particles can occupy the same space at the same time, but when gases mix

their particles are distributed regardless of orderly arrangement throughout the entire space to which they are confined.

Molecules and Atoms.—From the fact that solids and liquids are divisible into smaller and smaller particles as far as we can carry the division by mechanical means, it seems probable that the second assumption is the correct one, and that gases are made up of these small particles—the very smallest into which the substance can be divided without changing its nature.

Many of these particles we know to be compound. Thus water is composed of hydrogen and oxygen. The smallest possible water particle must contain hydrogen and oxygen. Steam, or water gas, is supposed to be made up of these smallest possible water particles, which are called water Molecules, and each of these is supposed to be composed of smaller particles of hydrogen and oxygen, called Atoms. Thus, whenever a particle exists by itself it is called a molecule; when it is combined with other particles to form a molecule it is called an atom. The same particle may be sometimes an atom and sometimes a molecule.

Chemical Evidence of Atoms and Molecules.—This theory is much strengthened by evidence derived from chemical reactions, from which we find that when substances combine to form a different substance, as hydrogen and oxygen to form water, they always combine in definite proportions, and that only a small number of definite compounds can be made from any two substances. Thus, two volumes of hydrogen gas always combine with one volume of oxygen gas to form two volumes of water vapor, three volumes of

hydrogen and one volume of nitrogen to form two volumes of ammonia gas, and the like. If gases were absolutely continuous bodies, we can see no reason why they should not combine in any proportions; but if they are made up of definite particles, then in any case of combination one or two or more of these particles must combine with one or two or more of the similar particles of another gas to form a single particle of the new gas which is being made from them.

Diffusion of Gases.—The molecular theory is also greatly strengthened by the rapidity with which gases mix when in contact with each other. Thus a little ammonia is spilled in one part of the room, and in a very short time its presence can be detected by its odor in all parts of the room. If a paper be dipped in hydrochloric acid and brought near the ammonia, the white fumes of ammonium chloride will show the presence of both gases in the air. This flowing of one gas into another is called Diffusion.

Diffusion of Gases through a Porous Partition.

LABORATORY EXERCISE 29.—A small porous cup, such as is used in many galvanic cells, should be fitted air-tight with a stopper through which is passed a glass tube of one or two millimeters bore and about thirty centimeters long. Prepare a hydrogen generator by fitting a flask with a tight cork through which pass two glass tubes. One, a short tube of four or five millimeters in diameter, should merely enter the neck of the flask and should project on the outside of the cork for the attachment of a rubber delivery-tube, while the other, a funnel tube, should reach nearly to the bottom of the flask. Put some scraps of commercial zinc which has not been amalgamated with mercury into the flask, cover them with water, and pour through the funnel tube enough sulphuric acid to cause a brisk chemical action. Invert a beaker or other vessel slightly larger than the porous cup over the top of the delivery tube, and allow the inverted

vessel to be filled with hydrogen. Pass the porous cup up under and into the vessel of hydrogen, letting the end of its tube dip in a vessel of water meanwhile.

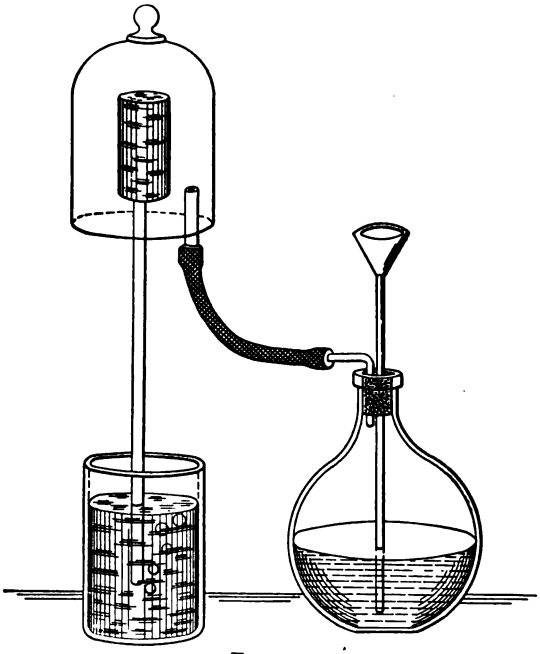


FIG. 29.

What evidence have you that the hydrogen enters the porous cup?

Remove the vessel of hydrogen from the porous cup. What evidence have you that hydrogen is escaping from it? What evidence that air is entering?

Experiments have shown that if the glass tube had been hermetically sealed the hydrogen would have entered the cup until its pressure upon the inside of the cup was as great as upon the outside. Then as many hydrogen molecules would pass out through the porous walls in a given time as would enter through them in the same time, and the pressures would remain constant.

It is known that air passes in and out through the porous walls in this way all the time, but when the cup was in hydrogen gas, the hydrogen entered faster than the air passed out. When it was removed the hydrogen escaped faster than the air entered. What proof had you that the air finally entered?

What reason have you for believing that the molecules of gases are in rapid motion?

Do the molecules of air or of hydrogen apparently move with the greater velocities?

Avogadro's Theory.—We have seen reasons for believing that all gases are very similar in their physical structure, and that all are made up of molecules which are constantly in motion, and which move with different velocities in different gases. Avogadro, an Italian physicist, in 1811, and Ampere, a French physicist, in 1814, arrived independently at the same theory to account for the similarity of the properties of different gases. They reasoned that if one gas were made up of large molecules far apart and another gas of small molecules close together, the laws of volume change for a change of pressure and temperature would not be the same in the two gases; hence that in equal volumes of gases which exert the same pressure at the same temperature there must be the same number of molecules at the same average distance apart. This is known as Avogadro's Law, and it is the assumption upon which the modern atomic theory in chemistry is based. It is generally stated, "*Equal volumes of all gases, measured under standard conditions of pressure and temperature, contain the same number of molecules.*"

This law can, of course, never be experimentally proved. The gas molecule is much too small to be seen with the most powerful microscope, even if it would remain at rest long enough to be observed, and

we have seen reasons for believing that it is always in rapid motion.

Cause of Gaseous Pressure.—If, as we believe, the molecules of gases are very numerous and in constant motion, they must frequently collide with each other and with the walls of the containing vessel. From the third law of motion, we know that the momentum of two colliding molecules must be the same after each impact as before, and if they are perfectly elastic, so that they rebound with a velocity, equal to the velocity of impact, as do the ivory balls in Exercise 18, their collisions will never bring them to rest. We have seen, too, that if an elastic particle strikes the wall of the containing vessel and rebounds with a velocity equal to its velocity of impact, its momentum before striking is mv toward the enclosing wall, its momentum after rebound is mv away from the enclosing wall, or $-mv$; hence it must have given to the wall a momentum $2mv$ in the direction of its motion before impact. This momentum would act as a pressure upon the enclosing wall.

Thus suppose a gas enclosed in a tube and supporting a column of mercury resting upon it. The mercury, on account of its weight, tends to fall to the bottom of the tube, but it is supported by the impacts of the gas molecules upon its lower side. Many millions of these molecules are supposed to impinge upon every square millimeter of the lower surface of the mercury every second, and each impact gives the mercury an upward momentum of $2mv$, where m is the mass of the impinging molecule and v its velocity. When a mercury column in a horizontal tube separates an enclosed gas volume from the outside air, the mercury column will

come to rest in the position where it receives as much momentum in one direction from the enclosed gas molecules as it does in the opposite direction from the outside air molecules.

If the enclosed gas is compressed so that the same number of molecules occupy a smaller space, more of them will strike the wall of the containing vessel in a given time, and will accordingly exert a greater total pressure upon it. Thus if the air column in the Boyle's tube be compressed to half its original volume, the mercury surface will be struck twice as often by the air molecules. For suppose a cylindrical tube one meter long with ends of some elastic substance, as ivory, and suppose an ivory ball to be moving lengthwise of the tube with a velocity of 50 meters a second. It will move the length of the tube fifty times in a second, and to do this it must rebound from each end twenty-five times. At each rebound it gives to the end a momentum $2mv$, and in each second a momentum of $50mv$.

Suppose the tube to be shortened to one half its length without interfering with the movement of the ball. Evidently each end of the tube will receive twice as many impacts as before, and consequently twice the outward momentum. If the tube contained a million ivory balls, the conditions would be practically the same; for while, owing to the collisions between the moving balls, the impacts upon the ends would not recur at regular intervals, still the same average number of impacts would occur in any considerable period of time. If instead of the million ivory balls the tube contained millions of millions of gas molecules moving with velocities of some hundreds of

meters a second, the conditions would correspond to what we believe to be actually taking place in a tube containing an enclosed gas.

We suppose a gas, then, to consist of a very large number of minute, independent bodies, having no action upon each other except when they collide, and acted upon by no force, so far as we know, except gravitation. In this view, the molecules of gases are as much independent bodies as are the planets, only they are confined to so small a space that they are constantly colliding with each other. If there were forces acting between them, then they would have accelerations toward or from each other, and their velocities would change with the distances between them.

Thus, suppose a quantity of gas to be enclosed in a tube provided with a tight-fitting piston, and let the piston be suddenly withdrawn until the space occupied by the gas is twice as great as before. We know that the gas will expand suddenly and fill the entire space. Suppose a repulsion to exist between the gas molecules while the gas is expanding. This repulsion will produce accelerations in all the molecules, and when the gas has occupied the larger volume the molecules will each have a greater velocity and a greater momentum than before. Then, while the molecules will have twice the distance to travel between collisions that they did in the smaller volume, they will travel this distance in less than twice the time and will accordingly strike upon the piston more than half as often as before, while at each impact they will give it a greater momentum than formerly. We see, then, that if the molecules of a gas repel each other, the pressure of the gas will not

decrease as fast as its volume increases. On the other hand, if the molecules attract each other, their velocities will be less when the gas has expanded to twice its volume, and the pressure will decrease faster than the volume increases.

Pressure Within a Gas Equal in All Directions.—This theory of the cause of gaseous pressure enables us to understand how the pressure at any point within a gas is equal in all directions, for, on the average, as many molecules are moving in one direction as in another. This is not true when currents are set up in the gas, as in that case the molecules have a greater average momentum in one direction than in any other.

Buoyant Force of a Gas.—It is a familiar fact that bodies lighter than the air are forced upward by the pressure of the air molecules under them. Thus a balloon filled with hydrogen will often rise to a great height. In this case, while the gas within the balloon exerts the same average pressure upon its walls as does the outside air, its downward pressure due to gravitation is less than that of an equal volume of the air. As long as this is the case, the air under the balloon will be under a less pressure than the surrounding air at the same level. This means that fewer molecules will be required to support the balloon than to support the downward pressure of the surrounding air. But as fast as the air expands and decreases its density under the balloon the surrounding molecules diffuse into this region and equalize the density. The result is that the balloon is pressed upward until it reaches an altitude where the density of the air is no greater than the density of the balloon and its enclosed gas.

Molecular Weights.

The density of oxygen gas is sixteen times that of hydrogen gas. If Avogadro's hypothesis be true, what is the weight of an oxygen molecule compared with that of a hydrogen molecule?

The hydrogen molecule is supposed to contain 2 atoms, and the weight of the hydrogen atom is taken as the unit of molecular weights. The molecular weight of hydrogen is accordingly 2; what is the molecular weight of oxygen?

Carbon dioxide gas has twenty-two times the density of hydrogen; what is its molecular weight?

Molecular Velocities and Pressure.—In our consideration of the ivory ball moving in the tube, we saw that if the length of the tube were shortened one half, the pressure upon the ends due to the impact of the ball was doubled. Suppose that instead of shortening the tube one half the velocity of the ball had been doubled. This would cause twice as many collisions with the ends of the tube as before, and each impact would give to the end of the tube twice as much momentum as before, hence the total pressure upon the ends of the tube would be four times as great as before. If the velocity of the ball were trebled, its pressure would be nine times as great as before.

The pressure would increase as the square of the velocity. Hence the pressure of a gas upon the walls of the enclosing vessel must vary as the square of its average molecular velocity.

The kinetic energy of a moving molecule must also vary as the square of its velocity. The average kinetic energy of all the molecules in a quantity of gas will accordingly vary as the square of their average velocity varies. Hence the pressure of a gas upon the walls of the enclosing vessel must vary as the average kinetic energy of its molecules varies.

Thus since the oxygen molecule is sixteen times as heavy as the hydrogen molecule, it must have sixteen times the momentum at the same velocity, and in equal volumes of hydrogen and oxygen if the molecules move with the same velocity, the oxygen will exert sixteen times the pressure of the hydrogen. When they exert the same pressure, the hydrogen molecules must have a velocity four times as great as the oxygen molecules. This makes their momentum at each impact one fourth that of the oxygen molecules, but gives them four times as many impacts in a unit of time, so that the total momentum given to the enclosing walls is the same in both. It also makes the average kinetic energy of the oxygen and hydrogen molecules the same.

The Kinetic Gas Theory.—The theory by which the pressure of a gas is explained by the momentum of its molecules is known as the Kinetic Gas Theory.

LIQUID STATE

PROPERTIES OF LIQUIDS

Cohesion.—We have seen that Boyle's Law and the laws of chemical combination can be explained on the hypothesis that a gas is merely an aggregation of independent elastic molecules in rapid motion, and that these molecules can only be held together in a mass by an external pressure applied to them, and that they are only held to the earth by the gravitation pressure. When gases are under very great pressures Boyle's Law does not apply to them. At a pressure which is different for different gases, and which varies with the temperature for the same gas, the volume of the gas begins

to decrease faster than the pressure increases, so that the product pv becomes smaller and smaller. This seems to indicate that when the molecules are brought close together there is an attraction between them, and that when they are held so close together that they do not get outside the range of this attraction a smaller pressure is necessary to confine them to this volume than would be necessary if the attraction did not exist. The name given to this attraction is Cohesion. If the volume be sufficiently diminished, this cohesion attraction increases enormously and a part of the gas changes into the liquid form. All gases may be changed into liquids in this way if only the temperature be not too high.

Vapor Pressure of a Liquid.—When a substance has become part liquid and part gas, any increase of pressure drives some of the gas into the liquid state, and any decrease of pressure allows some of the liquid to change into the gaseous state. *An external pressure is a necessary condition of the liquid state.* In some liquids, as in mercury, this external pressure may be very small. In other liquids, as ether or gasoline, it becomes very considerable. It is accordingly impossible to maintain a perfect vacuum above a liquid.

Measurement of Vapor Pressure of a Liquid.

LABORATORY EXERCISE 30.—The gas pressure which is necessary to permanently maintain the liquid state of aggregation is called the vapor pressure of the liquid. To measure it, proceed as follows:

Fill a Torricellian tube about a centimeter in diameter with mercury, invert it in the mercury cistern, hold it upright by means of a support and clamp, and measure the height of the mercury column. By means of a pen-filler or a bent glass tube pass a few drops of water into the bottom

of the tube under the mercury, taking care that no air bubbles enter. The water will rise to the top of the tube, and some of it will at once change into the gaseous state. The pressure of this gas causes a depression of the mercury column. What is the vapor pressure of water in centimeters of mercury from your experiment? What in dynes per square centimeter?

Refill the tube with mercury and repeat the experiment with gasoline. Lower your tube in the cistern, making the space above the mercury as small as possible. Make it as large as possible. Is the pressure the same in both cases? Give the vapor pressure of gasoline at the temperature of your experiment.

Comparison of Liquid and Gaseous Properties.— We have seen that liquids differ from gases in that their molecules no longer act like independent bodies, but are held together by an attraction or pressure called cohesion. No one has as yet been able to explain the cohesion pressure any more than the gravitation pressure. We only know that, while in some respects cohesion and gravitation are alike, they are not the same.

In their physical properties, liquids resemble gases in many particulars. Like gases they have very little elasticity of form, not enough to support any considerable pressure, and under the pressure of their own weight they accordingly take the shape of the containing vessel. Unlike gases, they offer very great resistance to compression, and it is believed that their molecules are so close together that they have very little opportunity for free motion. That they are still in rapid vibration we know from the fact that some of them are being continually bumped off from the surface with a sufficient velocity to carry them outside the range of cohesion attraction. It is only when the

molecules confined in the space above the liquid become so numerous that as many of them strike the liquid surface and enter it as are sent off from it in the same time that a constant volume of the liquid is maintained.

Elasticity of Form in Liquids.—That liquids do have some elasticity of form is shown from the following considerations: Small drops of mercury on a table or on an iron or glass plate take the spherical form. Falling rain drops are spherical. In the manufacture of shot, the molten lead is allowed to fall in small drops which take the spherical form and cool while falling. The molten beads on the end of a stick of sealing-wax or a glass rod take the spherical form. We accordingly infer that larger masses of liquid, if freed from the gravitation pressure, would take the spherical form.

Form of a Liquid Removed from Gravitation.

LABORATORY EXERCISE 31.—Pour a little water into a glass vessel (one with flat sides, as a flat-sided bottle, preferred), and on this water pour enough salad oil or other oil to form a mass about a centimeter in diameter. Then pour through a tube which reaches to the bottom of the water about one and a half times its volume of commercial (95 per cent) alcohol. This will mix gradually with the water and will form a liquid of about the same density as the oil. If too much alcohol be added, the oil globule will sink to the bottom, and can be made to rise in the liquid by adding a little water. If the oil rises to the top, add more alcohol, putting it in as near the bottom of the water as possible so that it may mix rapidly. A very few trials will enable you to prepare a solution in which the oil will float entirely submerged, as shown in Fig. 30.

What is the shape of the submerged oil globule? (Note that if you are looking through the curved sides of a cylindrical vessel the shape of the globule is distorted.)

Press it out of shape with a glass tube, and note the rate at which it returns to its original shape. Has it any elasticity of form? Has it enough to support its own weight? What reason have you for thinking that it is pressed upon equally on all sides by the surrounding liquid?

Note the appearance as if of a liquid skin over the surface of the oil, so that it acts like a rubber membrane filled with

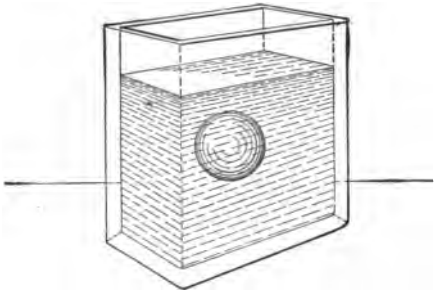


FIG. 30.

a fluid. If the oil were held together by the contraction of an elastic membrane, what shape would it take?

Contraction of Surface Film of Liquids.—Very many examples of the contraction of the surface film of water are familiar to every one. The hairs of your head cling together when wet, held by the water between them. Water may be carried in a sieve whose wires have been coated with paraffin so that the water will not cling to them, the weight of the water in the meshes of the sieve being supported by the strength of the surface film. An oiled needle may be floated upon water, held up by the surface film.

Experiments with Surface Films.

LABORATORY EXERCISE 32.—Perform some or all of the following experiments on the contraction of the surface film.

Blow a small soap bubble, and note its change in size while holding the pipe with the stem open to the air. Hold the end of the stem near a lighted candle and see if an air current is entering or leaving it.

Make a ring of wire about three or four inches in diameter and tie a loop of thread in it as shown in Fig. 31. Dip the ring into a soap solution and lift it out with a soap film clinging across it. The thread loop will then float about in the film. Break the film inside the loop by touching it with a hot wire, and explain what occurs.

FIG. 31.

Dip a funnel in a soap solution and take it out with a soap film across its mouth. Hold the funnel with the stem open and explain the movement of the film.

Pour enough water into a plate or flat-bottomed vessel to just cover the bottom with a thin layer. Pour a drop of alcohol upon this water. Does the alcohol increase or diminish the surface contraction of water?

Float a piece of paper on water and with a glass tube touch a drop of alcohol to one edge of the paper. Explain the movement of the paper.

Hold a small glass tube vertical in water and note the height at which the water stands in the tube. What supports the weight of the water column?

Fill a dry tumbler heaping full of water and then drop small stones or nails into the water as long as possible before the water overflows. What evidences do you see of a contracting surface film?

Formation of Surface Film by Cohesion.—All of the above experiments have shown an apparent contraction of the surface layer of water. This apparent

contraction of the surface film may be explained by the action of cohesion.

Thus, suppose a molecule within the body of a liquid attracted by all the surrounding molecules within the range of the cohesion attraction. Since these molecules are uniformly distributed about it, the molecule will have no tendency to move in one direction more than another, and its freedom of motion will in no way be affected by any molecules except those that may be in direct contact with it. With a molecule on the surface of the liquid the case is different; for since the attracting molecules are all below it, their resultant attraction is downward. This may also be true of the resultant attraction for molecules at small distances below the surface.

Thus, let *MN* in Fig. 32 represent the trace of a liquid surface and let *m* be a molecule below this surface. Let the circle about *m* as a center represent the circumference of the sphere of molecular attraction. That is, all molecules within this sphere will be near enough *m* to exert an attractive force upon it, while molecules outside of this sphere will have no influence whatever upon *m*.

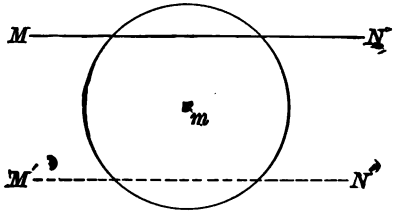


FIG. 32.

Let *M'N'* be a plane parallel to *MN* and as far below *m* as *MN* is above it. Then the forces exerted upon *m* by all the molecules between these planes will

just balance each other; that is, there will be always on opposite sides of m the same number of molecules at the same distances from m. The molecules in the part of the sphere below $M'N'$ will, however, exert an attraction upon m which will not be balanced by any corresponding attraction upward, since the corresponding part of the other hemisphere lies outside the liquid surface. The resultant of all the forces on m will accordingly be a downward pressure perpendicular to the liquid surface. This will be true for any molecule whose distance from the surface is less than the radius of the sphere of molecular attraction.

Influence of Curvature of Surface on Surface Tension.—On a convex surface the attraction of a molecule below the surface toward the surface will be less than on a plane surface, and on a concave surface it will be greater. Thus it will be seen that m_1 has fewer molecules attracting it toward the surface and m_2 a greater

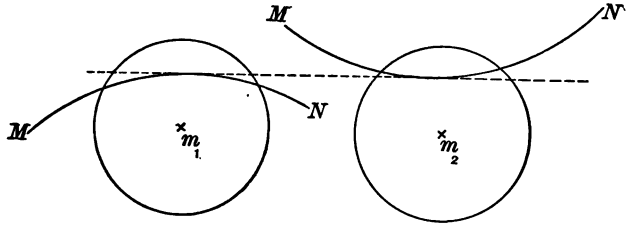


FIG. 33.

number than if they were at the same distance below a plane surface. The pressure of the surface film upon a liquid will accordingly be greater the more convex the surface, and less the more concave the surface.

Surface Tension on Soap Bubble.—In the case of a soap bubble, which is bounded by two films, the one

convex and the other concave, the pressure upon the convex outer surface will be greater than upon the concave inner surface, and the resultant of the two pressures will be an inward pressure upon the confined air. In the oil globule, the pressure of the surface film can be uniform only when the curvature of the surface is everywhere the same. Thus this pressure upon the whole free surface of a liquid has the effect of a contracting membrane which continually exerts a pressure upon the enclosed liquid.

Pressure of Surface Tension on Opposite Sides of a Soap Film.

LABORATORY EXERCISE 33.—In the case of a soap film on a wire frame, the pressure upon the air can never be greater

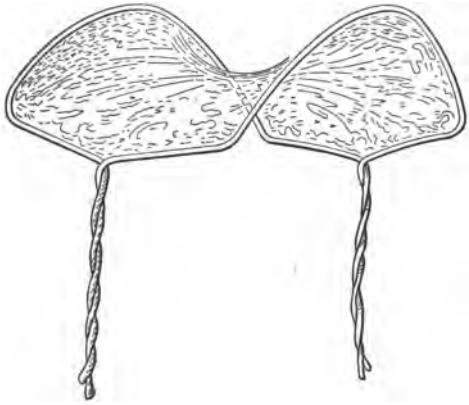


FIG. 34.

on one side than on the other, since the atmospheric pressure is the same in all directions. Consequently, when the film is made convex in one direction, it becomes concave in a direction at right angles to the convexity, and thus the increased pressure on the convex surface is balanced by a decreased pressure over the concave surface.

Make a rectangular wire frame, dip it into a soap solution

and take it out with a film across it. Bend the frame so that the film becomes convex on one side, as in Fig. 34, and note how the increased pressure of this convex film is balanced by the corresponding convexity at right angles to it of the film on the other surface. Observe the equality of the two curvatures at right angles to each other.

Measurement of Surface Tension. — The force exerted by a strip of unit width of the surface film of a liquid is called the Surface Tension of the liquid. The tables of surface tension of liquids generally give the weight in milligrams which can be supported by a strip of the surface film one millimeter wide.

Thus if a wire be bent in the shape *ABCD* and a

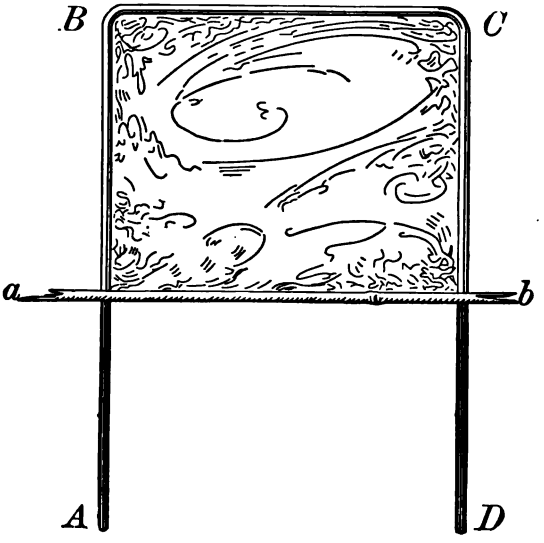


FIG. 35.

straight wire or straw *ab* be laid across it and a soap film be spread over the rectangle thus formed, the contraction of this film will pull *ab* toward *BC*. To

prevent this a weight can be attached to *ab* which will just balance the contraction. If the number of milligrams of weight required be divided by the number of millimeters between *AB* and *CD*, it will give the contractile force of the film in milligrams per millimeter in width of the film. But this contractile force is due to two surface films, one on each side of the soap film, hence the half of the force found will represent the surface tension of a soap solution.

Surface Tension in Capillary Tubes.—One of the best known methods of measuring surface tension is by the height of the column supported in small glass tubes called Capillary (hair-like) Tubes. Because capillary tubes have been used so much in measuring surface tension, the name Capillarity has sometimes been given to surface tension, and the measure of the surface tension of a given liquid is often called its Capillary Constant.

Measurements of Capillary Constants.

LABORATORY EXERCISE 34.—Select a clean glass tube of small bore and measure the diameter of the bore as accurately as you can by means of the vernier calipers. Place the tube vertical in a vessel of clean water. Raise and lower the tube, and observe whether the water column in it stands always at the same height above the water in the vessel. If it does not, the tube is not clean or is not of uniform bore.

Note that when the tube is raised, the part that is pulled out of the water remains wet, hence is covered by a surface film of water; consequently this surface film must stretch when the tube is raised and contract when it is lowered. Since the contracting film surrounds the inside of the tube, its width, if it could be straightened out to a plane surface, would be the inner circumference of the tube. This inner circumference is $2\pi r$, where r is the radius of its bore. Calculate the width of the film for your tube.

The force which stretches the film is the weight of the water column which it supports. The weight of this column

in grams is its volume in cubic centimeters times its density, or, in milligrams, its volume in cubic millimeters times its density. Its volume is found by multiplying its cross-section by its height. Its cross-section is πr^2. Its volume is $\pi r^2 h$, and its weight is $\pi r^2 hd$. Hence the surface tension is $T = \frac{\pi r^2 hd}{2\pi r} = \frac{hrd}{2}$.

Calling the density of water 1, what is its surface tension from your measurements?

Calling the density of alcohol .8, measure its Capillary Constant.

Assuming the density of a soap solution to be the same as that of pure water, is its capillary constant greater or less than that of water?

If the surface tension of chloroform is 2.73 and its density 1.48, how high will the liquid stand in a tube of 1 millimeter diameter?

Olive oil of density .9 stands 14.4 millimeters high in a tube of 1 millimeter diameter. What is its surface tension?

Our equation for surface tension is $T = \frac{hrd}{2}$. This may be written $\frac{2T}{d} = hr$. Since for a given liquid $\frac{2T}{d}$ is a constant, we can write $hr =$ a constant, or h varies inversely as r. Hence in any given liquid the heights of the capillary columns in different tubes are inversely as the radii of the tubes.

Pure water in a clean tube 1 millimeter in diameter will stand about 29 millimeters high. What is the diameter of the tube in which it stands only 7 millimeters high?

Surface Tension of Mercury.—Mercury will not rise in a glass tube because its surface tension is greater than its attraction for the glass. It accordingly stands lower in a glass tube than outside, and the top of the column in the tube, called the meniscus, is convex in mercury instead of concave as in water. Mercury drops are much heavier than water drops and yet maintain their spherical form much better, hence we

know that the surface tension of mercury is much greater than that of water. In fact, measurements by other methods have given the surface tension of mercury as 55, while the same methods gave for water only 8.25. Mercury clings to many metals as water does to glass, and in tubes of these metals the surface tension of mercury could be calculated from its capillary height.

If T is 55 and d 13.6, what would be the value of h in a 1 millimeter capillary tube to which mercury would adhere?

Magnitude of Cohesion.—It is impossible to measure the cohesion attraction between two liquid surfaces at molecular distances from each other, since we do not know how great the molecular distances are nor at what rate the attraction falls off with the distance. We know, however, from the work required to separate two such surfaces that the cohesion pressure between them is very great. Thus, if two glass plates having plane faces 1 centimeter square have a water film between them and are pulled apart, it requires the expenditure of 147 ergs of energy to separate them. If they could be kept absolutely parallel to each other, so that the two layers of water on the plates would be everywhere equally distant from each other, then 147 ergs of work would be done in moving one water surface against the force of cohesion to the distance at which cohesion ceases to act. This distance has been experimentally determined, and while the accuracy of the determination is not great, still the distance may be taken as about six millionths of a centimeter. If cohesion were a constant force acting through this distance, we could compute its value from the equation

$F = \frac{W}{S} = \frac{147}{.000006} = 24{,}500{,}000$ dynes, or the weight of about 25,000 grams.

Since, however, the force is zero at a distance of six millionths of a centimeter and increases to a maximum at the least distance of the surfaces from each other, it must be thousands of times this much at this least distance, so that it is probable that the two surfaces when in liquid contact are held together by a pressure of more than a ton to the square centimeter. Since the cohesion pressure is so great while the distance through which it acts is so small, it is supposed to decrease at a higher rate than gravitation does. The higher this rate, the greater is the attraction at molecular distance.

Compressibility of Liquids.—From the magnitude of cohesion, we should expect an enormous external pressure to be required to measurably compress a liquid volume. In fact, the earlier attempts at the compression of water led to the conclusion that water was incompressible. Later experiments have shown that all liquids are slightly compressible. Thus water at 0° C. has its volume decreased by about .00005 of itself for a pressure of one atmosphere. The atmosphere has its volume decreased one half by this pressure, hence air at standard pressure is about ten thousand times as compressible as water. Ether is nearly three times as compressible, and mercury is about one sixteenth as compressible, as water.

Viscosity.—It is a common observation that all liquids do not flow with equal freedom. This difference is very marked in two such liquids as water and molasses or honey. In fact, some liquids have considerable elasticity of form, and differ from solids only

in that this elasticity is not great enough to support the weight of the body.

The resistance which one liquid surface meets with in moving over another liquid surface is called Viscosity. Its cause is not well known. If the molecules of a liquid are perfectly spherical in shape, they can meet with little resistance in rolling over each other, even if they are in actual contact. If they are of irregular shapes, then they may move over each other with difficulty. It is known that all liquids can be compressed into smaller space under a sufficiently heavy pressure, hence their molecules must have some room for motion.

If cohesion is not, like gravitation, a force acting between the centers of gravity of the molecules, but, like magnetism, a force acting between definite points on the surface of the molecules, then the molecules will tend to cling together in strings, as would a mass made up of small magnets, and this would hinder the flow of the liquid. We shall see later that there is some ground for believing cohesion to act in this way.

The peculiar properties of many liquid films depend upon the viscosity of the liquid. Thus a soap film has less surface tension but greater viscosity than pure water. If a soap film be stretched across a wire frame and supported in a vertical position, the liquid will slowly run down to the bottom, and the soap film will grow thinner at the top. When it becomes too thin to support the weight of the liquid below, it will break at the top. The more viscosity the liquid has, the longer will the film stand before breaking. For the same reason, a soap bubble left standing becomes thin at the top and finally breaks.

In liquids having small surface tension and great viscosity air bubbles may stand for a long time without breaking. Such liquids are said to "froth" readily when shaken up with air.

Diffusion of Liquids.

LABORATORY EXERCISE 35.—Provide a wide-mouthed bottle or a deep tumbler with a siphon which reaches to within about one inch of the bottom. Fill the bottle nearly full of clear water and let some of it run out through the siphon. Close the siphon while full of water with a cork or a rubber tube and pinch-cock. Through a glass funnel-tube reaching to the bottom of the tumbler pour a strong solution of copper sulphate until it rises just above the end of the siphon. Open the siphon and allow the liquid to run out until there is a perfectly clear plane of separation between the heavier solution and the lighter water. Then close the siphon and allow the tumbler to stand undisturbed and note the rate at which the copper sulphate diffuses into the water above it. How does liquid diffusion compare in velocity with gaseous diffusion?

FIG. 36.

Do the molecules in a liquid retain their positions, or do they move about through the liquid?

Influence of Viscosity on Diffusion.—The rate of diffusion of liquids depends greatly upon their viscosity. If a strong syrup of sugar be placed in the tumbler instead of the copper sulphate, it will diffuse into the water much more slowly, and mucilage or glue will diffuse much more slowly than sugar.

Diffusion Through Porous Membrane.

LABORATORY EXERCISE 36.—Tie a piece of wet parchment paper tightly over the opening of a long-stemmed funnel or a thistle tube, pour a strong sugar solution into the funnel

until it rises into the stem, and suspend it in clear water so that the liquid will be at the same height inside and outside the tube. Leave it in this position, and determine if diffusion takes place through the parchment paper. Is the rate of diffusion the same in both directions? Does it require a greater pressure to force the water through the membrane into the solution, or out of it? Is cohesion apparently greater within the solution or within the pure water? Do you find evidence that the sugar diffuses through the membrane?

FIG. 37.

Osmosis.—The first observation on the diffusion of liquids through a porous membrane was made by the Abbé Nollet in 1748. He observed the different rates of diffusion of water and alcohol through an animal membrane, using a pig's bladder filled with alcohol and immersed in water. The name Osmose, or Osmosis, has been given to this membrane diffusion.

Osmotic Pressure.—In the Abbé Nollet's experiment the water entered through the walls of the bladder faster than the alcohol escaped and the bladder became distended by a great pressure. In the case of the sugar solution in water, if the solution had been placed in a closed vessel, the pressure exerted by the water diffusing into the solution would have broken the paper. The pressure of the enclosed fluid upon the walls of the containing vessel is called Osmotic Pressure.

From the importance of osmotic action in physiological processes, such as respiration, secretion, excretion, and the like, and from the fact that some recent

physical theories attach great importance to it, the phenomenon of osmotic pressure has for several years attracted much attention. It has been found possible to prepare partitions which will allow only water to diffuse through them. This is done by precipitating some insoluble substance, as Baric Sulphate or Copper Ferrocyanide, within the walls of a porous cup. By means of these so-called semi-permeable cells much greater osmotic pressures can be observed than in cells which allow both substances to diffuse through them.

Thus water will diffuse into a one per cent solution of saltpeter until it produces an osmotic pressure of more than three atmospheres. This pressure, while very considerable, is, we know, very small as compared with the total cohesion pressure.

Evaporation.—It has already been observed that an external pressure is necessary for the maintenance of the liquid state. This pressure must be a pressure due to the vapor of the liquid. When the molecules on the surface of a liquid are driven off by the impact of molecules below them, they at once become free gas molecules, and if they escape into the air they are knocked about by the air molecules and are not likely ever to return to the liquid surface again. If they escape into an enclosed space above the liquid, this space finally becomes so filled with them that as many strike the liquid surface and enter through it as escape from it in the same time. Then, though the exchange of molecules between the liquid and its vapor is constantly going on, the total quantities of liquid and vapor remain the same. This escape of molecules from the liquid surface is called evaporation. It goes

on at all temperatures, but much more rapidly at high temperatures than at low.

Evaporation takes place on a large scale all over the surface of the earth. The rain which falls upon the earth has all been raised by evaporation.

If a basin of water with vertical walls be exposed to the air for several days, the depth of water evaporated in a day can be easily measured.

Boiling.—When ordinary water is poured into a glass it always contains many small air bubbles. These bubbles usually cling to the sides of the glass, and when expanded by heat they can be easily seen. Evaporation must take place into these bubbles as into the outside air. As the temperature of the water is raised, its vapor pressure in the air bubbles increases. As long as this pressure is less than the pressure of the external air on the surface of the water the bubbles do not expand and break through the water into the outside air. When the pressure within the bubble becomes greater than the atmospheric pressure, the bubbles expand and break and their vapor escapes into the air. This process is called boiling.

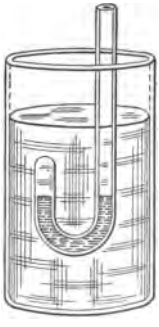


FIG. 38.

Vapor Pressure of a Boiling Liquid.

LABORATORY EXERCISE 37.—A J-shaped tube about a centimeter in diameter with the short arm closed about four or five centimeters above the bend has the short arm and the bend filled with gasoline or some other volatile liquid, so that no air remains above the liquid in the closed arm. A vessel of boiling water is carried to some distance from a flame, and the tube of gasoline is lowered into it. The gasoline boils, and while some of its vapor escapes through the open arm into the

air another part gathers in the closed arm. How can you know when the vapor pressure in the closed arm is equal to the atmospheric pressure? How does the vapor pressure of boiling gasoline compare with the atmospheric pressure?

Condensation.—In your experiments on vapor pressure you saw that the pressure of a vapor above a liquid is independent of the space which it occupies. It must be, then, that any increase of pressure drives some of the molecules into the liquid state, as otherwise the pressure would increase when the volume decreased. This change from the gaseous to the liquid state is called condensation. It may be effected by increasing the pressure on a vapor or by lowering its temperature. It will be considered more fully under the subject of Heat.

MECHANICS OF FLUIDS

Conditions of Equilibrium in Fluids.—We have seen that a pressure applied to any part of the body of a gas is transmitted very soon to all parts of the gas. That this transmission is not instantaneous can be seen in blowing a soap bubble. If the air is blown in under great pressure, the bubble may become elongated, but it assumes the spherical form almost immediately after the pressure is removed. It would, accordingly, be impossible for a confined gas to maintain a greater pressure on one part of its surface than on another, because the molecules, being free to move, would move into the region of least pressure until the pressure was equalized. The only exception to this is the case of the gravitation pressure. A gas in an enclosed vessel presses downward more than upward by an amount equal to its weight.

Since the molecules of a liquid are also free to move about, they will likewise move toward regions of least pressure until the pressure is equalized. Thus all liquids sooner or later come to rest with their upper surfaces level, so that the gravitation pressure, the atmospheric pressure, and the surface tension are all uniform over the surface. In mobile liquids, like water, this position of equilibrium is soon reached. In viscous liquids, like tar, it may not be reached for a long time; but unless the liquid has sufficient rigidity to resist permanently an external pressure, the pressure will finally be equalized throughout the liquid. One condition of equilibrium in a liquid or gas is, then, that the external pressure (not counting the pressure due to its own weight) must be everywhere the same on equal areas of its surface.

Water or any other mobile liquid will accordingly stand at the same level in communicating vessels or tubes, so long as the tubes are not small enough for the surface tension to appreciably raise the water surface within them.

Transmission of Pressure.—Suppose two communicating cylinders of water, one having a cross-section of 1 square centimeter, and the other having a cross-section of 100 square centimeters. The water will stand at the same height in both cylinders. Suppose 1 centimeter in depth of water to be added to each cylinder. The water will still be at the same level in both cylinders. Hence the pressure of 1 cubic centimeter of water in the small cylinder balances the pressure of 100 cubic centimeters of water in the larger cylinder. That is, an additional pressure equal to the weight of 1 cubic centimeter (equals 1 gram) of water

has been added to every square centimeter of free surface of the water.

Suppose that instead of pouring water into the larger cylinder a tight-fitting piston had been pushed down until it was just in contact with the water, and then one cubic centimeter of water had been poured into the smaller tube, what would have been the upward pressure of the water per square centimeter against the piston in the large cylinder?

What would have been the total upward pressure against the piston?

Suppose that both tubes had been fitted with pistons, and that by pressing down upon the small piston a weight had been raised on the large piston. What would have been the mechanical advantage of the small piston? Through what distance would it have moved to raise the large piston one centimeter? Would the general law of machines apply to this machine?

The Hydraulic Press.—The machine just described is known as the Hydraulic Press. It was invented by Bramah in 1796. The accompanying figure is from a book of that period.* The explanation given is as

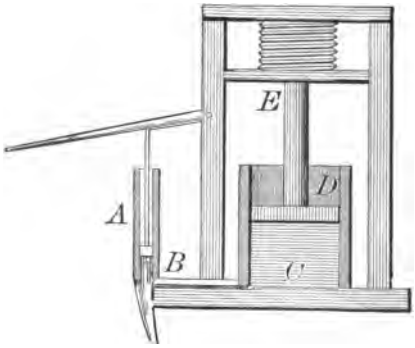


FIG. 39.

follows: "The pump *A* forces the water through the pipe *B* into the barrel *C* in which it acts very power-

* Dr. Thomas Young's Lectures on Natural Philosophy, Vol. I, p. 781.

fully on the large piston *D*, and raises the bottom of the press *E*." These presses are sometimes made very strong and capable of exerting enormous pressures.

Gravitation Pressure Within a Liquid.—We have seen that in the case of the atmosphere the weight of the upper air exerts a pressure upon the air near the earth equivalent to about 15 pounds to the square inch. We know that within the body of the air this pressure must be equal in all directions, as the most fragile soap bubble retains its spherical form. We have also seen that bodies lighter than air may be driven upward by this pressure.

We have seen that in mobile liquids any external pressure upon the surface must be the same over the whole surface to prevent motion in the liquid. The same thing must, accordingly, be true of the pressure exerted by the weight of the upper layers of the liquid; hence at a given depth below the surface of a liquid at rest the pressure must be everywhere the same. Since this pressure is determined by the weight of liquid above it, it must increase as the depth of the liquid increases.

Measurement of Gravitation Pressure Within a Liquid.

Laboratory Exercise 38.—A glass tube about one centimeter in bore, shaped like a Boyle's tube, but open at both ends, is filled with water to a depth of two or three inches on each side of the bend. Pour a tall cylinder, as a hydrometer jar, nearly full of kerosene or gasoline and lower this tube into it until the top of the open tube is below the surface of the liquid in the cylinder, as shown in Fig. 40. Note the rise of the water in the long arm of the tube. What causes this rise? Raise and lower the tube in the liquid and note the change of height in the column of water. Make several measurements of the distance from the surface of the

water in the short arm to the surface of the liquid in the cylinder and to the surface of the water in the long arm. How does the pressure of the liquid upon the water surface vary with the depth? Which is heavier, the liquid in the vessel or the water in the tube? If one cubic centimeter of water weighs a gram, what is the downward pressure of the other liquid

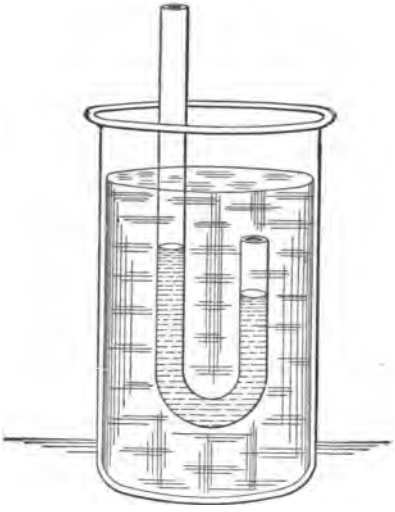


FIG. 40.

in grams per cubic centimeter? What is the density of the other liquid? Measure out in a graduated cylinder fifty cubic centimeters of the liquid and weigh it on the platform balance. What was the error of your estimate of its density?

Pressure upon any Point within a Liquid is the Same in All Directions.—We have seen from the preceding experiment that the gravitation pressure within the body of a liquid is proportional to the depth below the surface. We saw in the case of the oil globule floating in another liquid that its shape was spherical, hence the liquid pressure upon it must have been equal in all directions. We know, too, that if this had not been the case the oil would have moved away from the

greater pressure and toward the less. The same thing would be true of any particle within the water, hence the conditions of equilibrium in a fluid, either gas or liquid, are that the pressures upon any particle within the fluid must be balanced on all sides. This would necessarily follow if, as we suppose, the pressure upon any surface is due to the momentum of the molecules striking against it, for as many of these molecules must at any time be moving in one direction as in another.

Downward Pressure of a Liquid Column Independent of its Shape.—That the downward pressure within a liquid is independent of the shape of the liquid column above the point where the pressure is measured follows from the same considerations. To prove this conclusion experimentally, proceed as follows:

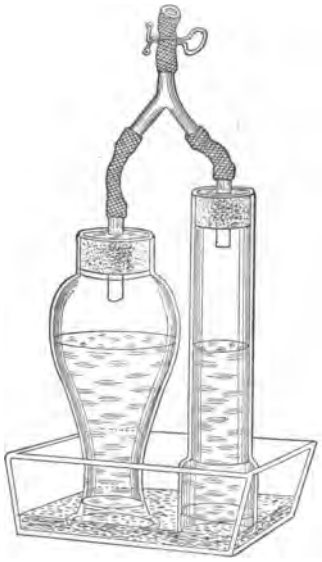


FIG. 41.

LABORATORY EXERCISE 39.—Two lamp chimneys of different shapes are provided with tight-fitting corks in one end through which pass short glass tubes. Connect these by means of short pieces of rubber tubing with a lead or glass T tube. Place the lamp chimneys with the open ends in a vessel of water, and suck air out of them until they stand about half full of water.

What supports the water columns in the lamp chimneys? Is the pressure which supports the two columns the same on each square centimeter of surface? Why?

Does the downward pressure of a liquid column depend upon the shape of the column or only upon its height?

The downward pressure of a liquid upon a given surface depends upon three things: (*a*) The area of the surface; (*b*) The height of the liquid column; (*c*) The density of the liquid. State the law so as to include these three conditions.

Pressure of a Liquid upon the Sides of the Containing Vessel.—Since the pressure at any point within a liquid at rest must be equal in all directions, the pressure of any liquid particle against the side of the containing vessel must be the same as the downward pressure of this same particle. Hence the lateral pressure upon any very small area of the side of the vessel must be the same as the downward pressure upon an equal area at the same depth.

Average Pressure.—The total pressure upon a given surface divided by the area of the surface is called the Average Pressure over the surface.

The average pressure against a square centimeter of surface in the side of a vessel is the pressure due to the depth of the liquid at the middle point of the area considered. Thus, if a vertical strip one centimeter wide on the wall of a vessel containing water be considered, the pressure upon the first square centimeter measured downward from the surface of the liquid is .5 gram. That is, the lateral pressure of the liquid one-half centimeter below the surface is one-half gram per square centimeter. Upon the next square centimeter below this the lateral pressure is one and a half grams. What is the total pressure upon such a strip reaching six centimeters below the surface of the water? What is the area of this total surface? What is the average pressure upon it? At what depth is the downward pressure equal to the average lateral pressure?

PROBLEMS.—What is the average lateral pressure upon the wall of a vessel containing water to the depth of ten centimeters?

What is the total lateral pressure upon a beaker ten centimeters in circumference containing water to a depth of eight centimeters?

What is the total pressure upon the sides of a cubical box one meter on each edge filled with water? What is it adding the atmospheric pressure? Does the box need to be made stronger on account of the atmospheric pressure?

If a cubic foot of water weighs $62\frac{1}{2}$ pounds, what is the lateral pressure per square foot upon a dam containing water 50 feet deep?

To what height would the mercury stand in a barometer tube 50 feet below the surface of water?

If the cubical box one meter on each edge be entirely closed and filled with water and then have a tube one centimeter square inserted in its top and filled with water to a depth of one meter, what additional pressure in grams per square centimeter will be caused by the water in the tube? What will now be the total water pressure upon the six faces of the box?

Buoyant Force of a Liquid.

Suppose one cubic centimeter of water at any depth below the surface to become solid without changing its volume or weight, how much would the upward pressure of the liquid water upon it exceed the downward pressure?

A cubical block one centimeter on each edge is placed with its top face horizontal and four centimeters below the surface of water in a beaker. What is the downward pressure of the water upon its top face? What is the upward pressure of the water against its bottom face? What must be the weight of the block to just float in this position? If it weighs five grams and is supported by a thread, what weight does the thread support? Will this weight be different when the block is ten centimeters below the surface?

If the block were a rectangular prism having ends of one-fourth square centimeter area and a height of four centimeters, its volume would be one cubic centimeter. If it were supported vertically in the water, what would be the buoyant force of the water upon it? What would be the buoyant

force of the water upon it if it were lying on its side in the water?

What volume of water weighs as much as the loss of weight of the block in water?

Loss of Weight of a Body Immersed in Water.

LABORATORY EXERCISE 40.—Attach a thread to a piece of metal or other solid having a volume of several cubic centimeters. Lower the solid into a graduated cylinder of water and note the increase of volume when the solid is immersed in the water. Record the volume of the solid.

Place the platform balance on a box or a board supported on blocks through which two holes have been bored at a distance apart equal to the distance between the centers of the pans. From the ends of the lever arms directly below the center of one of the pans, attach the thread by means of a bent-wire hook, and let the solid swing just above the table. Counterpoise by means of weights on the other pan.

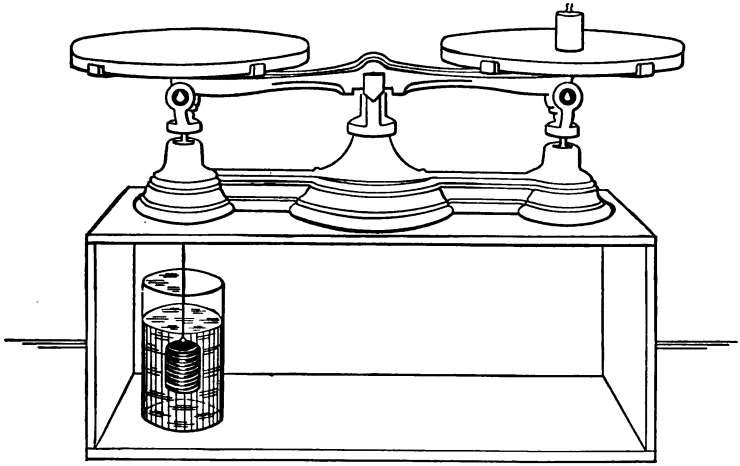


FIG. 42.

Place a beaker of water so that the solid will be suspended immersed in the water, and add known weights to the balance pan until equilibrium is produced. These weights represent the loss of weight of the solid in water. Record

this loss of weight. How does it compare with the weight of a volume of water equal to the volume of the body?

Place the beaker of water on one balance pan and counterpoise with weights on the other. Suspend the solid just used so that it will swing immersed in the water without touching the beaker. What additional weight does the immersed body give to the water? How does the gain in weight of the water compare with the loss of weight of the body? How many cubic centimeters of water would have to be poured into the beaker to increase its weight as much as it is increased by the immersed body?

A tin can or other vessel holding about a pint has one edge bent down at the top forming a lip, and has a spout two or three inches long soldered to this lip to carry off the overflow. Place this can on the balance with the end of the spout projecting beyond the side of the pan, and set a vessel on the table beside the balance to catch the overflow. Fill the can with water until some overflows, and then counterpoise it. Attach as large a solid as can be conveniently used to a thread and lower it into the water until it is immersed, allowing the water to overflow into an empty vessel. Have you changed the weight of the can of water? Why?

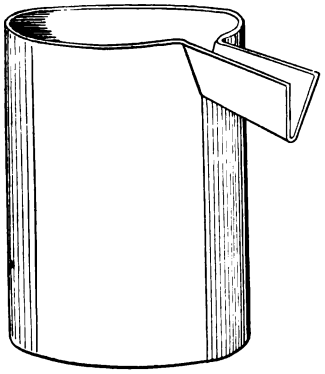


FIG. 43.

Weigh the overflowed water and, assuming that one cubic centimeter of water weighs a gram, calculate the volume of the body from the weight of the displaced water. Weigh the solid and calculate its density.

Floating Bodies.

LABORATORY EXERCISE 41.—Weigh a small block of wood. Place a vessel of water upon one pan of the balance, counterpoise it, and place the block in the water. Does it add its own weight to the weight of the water?

Place the overflow vessel upon the balance. Fill with

water and counterpoise. Place the block in the water and catch the overflow in an empty vessel. What weight of water has apparently overflowed? Weigh the overflow and see if your conclusion is correct. A floating body displaces what weight of water?

Principle of Archimedes.—About 250 B.C., Archimedes, in Sicily, stated the principle which has since been known by his name. It is as follows: "*A body suspended in a fluid apparently loses as much weight as is equal to the weight of the quantity of fluid which it displaces.*" (Does this statement express the results of the preceding experiments?)

This gives us a very accurate method of determining the volume of a body. With a good balance the loss of weight of a small body immersed in water can be determined to within a milligram, which corresponds to a volume of .001 cubic centimeter. No other method of measuring the volume is so accurate as this.

Density and Specific Gravity of Liquids and Solids.—The specific gravity of liquids and solids is generally referred to water as a standard. This would make the specific gravity of water equal to unity Since one cubic centimeter of water weighs very approximately one gram, the density of water in grams per cubic centimeter is also equal to unity. Hence the density of any body expressed in grams per cubic centimeter and its specific gravity referred to water are numerically equal. If the density were measured in pounds per cubic foot, the density of water would be 62½ and consequently would not be numerically the same as its specific gravity.

Measurement of Density by Principle of Archimedes.

LABORATORY EXERCISE 42.—Suspend a piece of metal or a

stone below the balance pan and counterpoise as in Exercise 40. Place a beaker of water so that the solid is immersed in it, and find its loss of weight. Calculate the volume of the solid. Find its loss of weight in kerosene or some other liquid, and calculate the density of this liquid.

Weigh the solid and calculate its density.

Place the overflow vessel full of water so that the water will flow over into a counterpoised vessel on one pan of the balance. Place a block of wood on the water and determine its weight from the weight of the overflow water. With a long pin or needle force the block below the surface of the water, and calculate its volume by means of the overflow water. Calculate the density of the block.

Use of Specific-gravity Bottle.

LABORATORY EXERCISE 43.*—Find the cubical content of a specific-gravity bottle by weighing first the bottle and then the bottle filled to a marked height with water. Pour out the water and fill to the same height with another liquid and weigh again. Calculate the density of the other liquid.

Weigh out about 20 grams of shot and pour into the bottle. Fill with water to the previous mark and weigh. What weight of water does the bottle contain? What volume of shot does it contain? What is the density of the shot?

PROBLEMS.—How much more will a liter of water weigh in a vacuum than in the air?

A piece of brass weighs 85 grams in the air, 75 grams in water, and 77 grams in another liquid. What is the volume of the brass? What is its density? What is the density of the other liquid?

An iron ball (density 7.5) weighs 1000 grams in air. What will it weigh in kerosene of density .8?

The density of cork is .24. What will be the loss of weight in air of one kilogram of cork?

Calculate the displacement of a balloon which with its contents weighs 100 pounds and by which you could be raised from the ground.

* This exercise has no special bearing upon the theory of Physics, and may be omitted if desired.

SOLID STATE

PROPERTIES OF SOLIDS

Change from Liquid to Solid State.—Any known liquid may be changed to the solid form by lowering its temperature sufficiently. Thus, water when sufficiently cooled becomes ice. Mercury solidifies at a temperature lower than the freezing-point of water, and the other common metals at much higher temperatures. The gases of the atmosphere change to liquids and then to solids only at very low temperatures.

As the temperature of a liquid is lowered its viscosity increases. In some substances this change is continuous until a condition of rigidity is reached and we call the substance a solid.

In other cases, solidification begins at certain centers (perhaps upon other solid particles already within the liquid), and spreads through the liquid. In this case, the particles of the liquid which come to rest in the solid form are held to the surfaces of the solid masses already formed.

Structure of Solids.

LABORATORY EXERCISE 44.—Melt a piece of sealing-wax in a convenient vessel and allow it to solidify by cooling. Note that it changes gradually from a liquid to a solid, becoming more and more viscous until finally, while still soft, it may be pressed into a form which it will permanently retain. After it has solidified it is seen to be without any visible structure, any one particle appearing exactly like any other.

Solid bodies which, like sealing-wax and glass, show no regular internal structure are said to be Amorphous.

Melt a quantity of sulphur in a glass or porcelain vessel, and after it has become a clear liquid set it aside and allow

it to cool slowly without disturbance. When it is about half solidified pour off the remaining liquid and note the structure of the solid part. It will be seen to be made up of small bodies called crystals. Examine these and determine if they bear any general resemblance to each other.

Bodies which, like sulphur, solidify in the form of crystals are called Crystalline. The crystalline form is much more common in nature than the amorphous.

There is still another form of solid structure known as the Cellular. This includes the solid parts of plant and animal bodies, and is built up from the living cell.

Properties of Crystalline Solids.

LABORATORY EXERCISE 45.—Examine specimens of different crystalline substances and notice that in general crystals are bounded by plane faces which make definite angles with each other in all crystals of the same substance. Notice that a block of mica is bounded on two opposite faces by these crystalline planes, and that it can be separated into very thin parallel sheets, each sheet having naturally polished surfaces.

These natural planes of separation in a crystal are called Cleavage Planes. They indicate that the molecules of a crystal are not spaced at equal distances in all directions.

Look through a crystal of Iceland spar at a pin-hole in a piece of cardboard held against one side of the crystal. Note that in some positions you can apparently see two pin-holes, and that the apparent distance between them varies with the direction of sight through the crystal.

Look at a lighted window through two tourmaline crystals mounted in the tourmaline tongs. Rotate one of the crystals around the line of sight and note that in certain positions it shuts off the light which comes through the other crystal, while in other positions it allows it to pass through.

All of these observations indicate that in crystals some of the physical properties are different in different directions through the crystal. The same thing is true for many other properties. Thus if a sphere be turned out of a crystalline substance and be immersed in a liquid and put under heavy pressure, though the pressure is necessarily equal in all directions, the compression will be greater in some directions

than in others, showing that the elasticity of compression of the crystal is different in different directions.

If a sphere be turned from a crystal and immersed in an acid solution which will etch away the crystal, the crystal will not remain spherical, but will be gradually etched down to its original form, showing again that cohesion is different in different directions through the crystal.

Isotropic and Anisotropic Bodies.—Bodies in which all physical properties are the same in all directions through the body are said to be Isotropic. Bodies in which some of the physical properties vary with direction are called Anisotropic.

Crystals are anisotropic bodies. Amorphous solids, as well as liquids and gases, are isotropic.

Equilibrium of Solid and Liquid States.—If a vessel containing broken ice and water be placed where it can neither receive nor give off heat, the total quantity of ice and water will remain the same. It is believed that in this condition molecules are constantly escaping from the ice to the water, and other molecules are constantly striking against the ice surfaces and being held fast by cohesion. As long as the total quantity of heat in the whole mass remains unchanged, as many molecules must go into the solid state as into the liquid state in the same time.

Cohesion between Solid Surfaces.

LABORATORY EXERCISE 46.—Press together tightly with a rotary motion of one surface upon the other two plane, polished glass surfaces, and note the force required to pull them apart.

Do the same for two freshly cut plane lead surfaces. What apparently holds the surfaces together? (N.B. The surfaces are held together with a very considerable pressure in the exhausted receiver of an air-pump. What possible cause of the pressure does this exclude?)

In welding metal surfaces they are first heated to soften the metal and are then hammered into close contact with each other, after which they cling together on account of the cohesion between their molecules.

FRICTION BETWEEN SOLID SURFACES

Cause of Friction.—The resistance which one solid surface meets with in moving over another is called Friction. Friction is always accompanied by a wearing away of the surfaces, and is in large part due to the force required to break off the small projecting particles from the surface. Polishing the surfaces of contact accordingly reduces the friction between them.

When surfaces are rough there is no regularity in the friction between them, but the friction between smooth surfaces follows definite laws. If the surfaces are highly polished and of the same material (as in Exercise 46), the cohesion is often so great between them that one surface can scarcely be moved over the other at all.

Coefficient of Friction.

LABORATORY EXERCISE 47.—For experiments on friction a straight-grained pine board about a meter long and 20 or 30

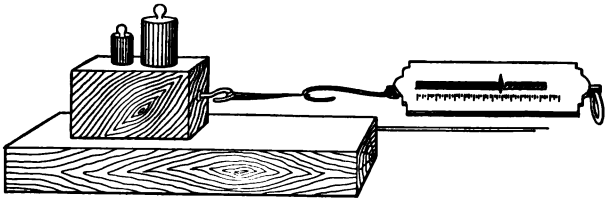


FIG. 44.

centimeters wide should have one face carefully planed and sandpapered. This board should be kept only for friction experiments.

Several blocks of different kinds of wood about 20 by 10 by 5 centimeters should be prepared and carefully smoothed. These may be cut from 2 × 4-inch or 2 × 6-inch scantling, and should have screw hooks fastened into the center of one end.

Place the board on a table with the smooth face upward, lay one of the blocks on its smooth side on the board, place a weight of several pounds or kilograms on the block, and by means of a spring balance, weighing to ounces or other small units and attached to the hook by a cord, pull the block with uniform motion along the board and note the reading of the balance. Why is it important that the cord should be kept parallel to the board? After the block is once in motion, does the balance indicate a greater pull when the block is drawn rapidly along the board than when it is drawn slowly? Why should the balance reading be greater when the motion of the block is being accelerated?

Turn the block on edge, load it with the same weight as before, and repeat the experiment. Does the amount of friction vary with the area of the contact surfaces?

Lay the block on its side and find the force required to pull it with uniform speed under different loads. Tabulate your results, giving the load (including the weight of the block), and the pull on the balance for several different loads.

The coefficient of friction has been defined as the quotient of the force parallel to the surfaces of contact divided by the total pressure normal to these surfaces. In your experiments it is the pull on the balance divided by the total weight of the block and its load expressed in the same units. Calculate this coefficient for all of your experiments. What is the average of your determinations?

Determine the coefficient of friction between surfaces of two different kinds of wood.

Coulomb's Laws of Friction.—The first careful measurements of friction were made by Coulomb in 1781. Coulomb's Laws of Friction may be stated as follows: *The friction between two solid surfaces is independent of the extension of the surfaces of contact, is proportional to the pressure, and independent of the velocity of motion.* Are these statements borne out by your experiments?

The above laws are subject to considerable modification. We have seen that when the surfaces are brought near enough to allow cohesion to act between them the friction may depend greatly upon the area of the surfaces of contact.

If your board be rested only upon supports at the ends and a heavy load be drawn lengthwise of it, the board will bend downward in the middle, and the load will have to be drawn up-hill. The deformation of a surface under a heavy load is one of the principal causes of the resistance to motion along it.

Rolling Friction.—When a cylinder or a sphere is rolled over a plane surface there is no slipping of one surface upon the other, and consequently no friction of the same kind as between sliding surfaces. In this case, the principal resistance to motion is in the deformation of the surface. Thus a heavy cylinder rolling over a flat surface always causes a depression in the surface, and the cylinder must be constantly rolled up-hill. If this depression is great enough to cause a slipping of the cylinder upon the flat surface, ordinary friction will result.

The freedom from ordinary friction in rolling motion has led to the extensive use of ball bearings in bicycles and other machines.

The friction of a shaft in its bearing is not rolling friction. In this case, the shaft rolls upward on one side of its bearing until it can roll no higher and then slips on the side of the bearing.

Use of Lubricants.—Since the viscosity between liquid surfaces is less than the friction between solid surfaces, liquids are frequently placed between solid surfaces to lessen their friction. If the moving surface

could be entirely floated upon the liquid, solid friction would be entirely replaced by viscosity, but this is not often practicable.

Sometimes amorphous solids, as graphite, are used as lubricants. In graphite the cohesion between the small particles is so slight that the friction between two surfaces covered with graphite is much diminished.

ELASTICITY OF SOLIDS

Elasticity of Compression.—Solids, like liquids, offer great resistance to compression of volume. This compressibility has been accurately measured in only a few solids. In general, solids are less compressible than liquids. Glass is about one sixteenth as compressible as water, or about as compressible as mercury. Brass, copper, and steel are less compressible than glass.

It has already been mentioned that the compressibility of crystals varies in different directions through the crystal, so that no definite coefficient of compressibility can be given for crystalline solids.

Rigidity.—In addition to having a greater elasticity of volume than liquids, solids also have elasticity of form, or rigidity. The magnitude of rigidity varies greatly in different solids, being very great in steel and small in India rubber or jelly.

The rigidity of a body may be measured by the force required to bend it, to stretch it, to twist it, or to compress it in one or two dimensions. According as we use one or the other of these methods we get different numbers to represent the rigidity of a body.

Hooke's Law.—All measurements of the elasticity of solids are based upon Hooke's Law, stated in 1678,

according to which the amount of change of shape is proportional to the distorting force; i.e., the elongation is proportional to the stretching force, and the like. This law is now known not to apply accurately to stretching forces, and probably does not apply with perfect accuracy to distorting forces of any kind. Within the limits of ordinary experimental accuracy, however, Hooke's Law applies to rigidity just as the similar law of Boyle applies to compressibility of gases. Thus, if a wire one meter long be stretched one millimeter by a weight of one kilogram, it will be stretched two millimeters by a weight of two kilograms. If a beam supported at its ends be depressed one inch by a load of one hundred pounds, it will be depressed two inches by a load of two hundred pounds.

Limits of Perfect Elasticity.—We have defined as "perfectly elastic" those bodies in which a given pressure always produces the same change of form or change of volume. In this sense the rigidity of most solids is only perfect within comparatively narrow limits. If the body be stretched or bent beyond these limits, it is either broken or has its shape permanently changed.

If a body breaks under a pressure before it has its shape permanently changed, it is said to be *brittle*. If it assumes a permanent change of shape, it is said to be *malleable* or *plastic* or *ductile*. Metals are usually malleable, but may be made brittle by hardening.

Steel has the widest range of perfect elasticity of any known metal. The steel piano wire which is used in deep-sea soundings stretches by one eighty-sixth of its original length before it becomes permanently elongated. In cork, India rubber, and jellies the limits of

perfect elasticity are proportionally wider. An India-rubber band may stretch to eight times its original length and return to almost its original length when the stretching force is removed. The limits of perfect elasticity of lead and putty are very small.

The elasticity of a body is weakened by repeated stretching or bending. A vibrating tuning fork comes to rest more quickly after having been kept in vibration for a long time than after a period of rest.

Change of Density in Solids.—Malleable metals may have their densities considerably changed by hammering, compression, or stretching. The density of gold is increased in coining by over a half of one per cent, and the density of silver is increased in the same way by more than four per cent. The density of a wire may be decreased by permanently stretching it.

Elastic Impact.—We may now see how two elastic balls may rebound after collison with each other. In striking against each other the balls are at first flattened, but on account of their rigidity they quickly return to their original shape. In doing this they mutually push each other apart. If their elasticity is perfect, they do as much work upon each other in recovering from the distortion as while the distortion was taking place, consequently they have the same momentum and the same kinetic energy after impact as before. If not perfectly elastic, some work is used up in permanently changing the shape of the balls, and while their momentum after impact is the same as before, their kinetic energy may be less. Thus two equal balls of putty moving in opposite directions with equal velocities will cling together and come to rest

after collision. Since the algebraic sum of their momentums before impact was zero, it remains unchanged, but their kinetic energy has disappeared. Has the energy done work upon the balls?

PART III

HEAT

ORIGIN OF OUR KNOWLEDGE OF HEAT

The Temperature Sense.—Our knowledge of heat is derived in the first place from the Temperature Sense. A large number of highly specialized nerves, called Temperature Nerves, are distributed to the skin over the whole body, and these enable us to tell whether objects which come in contact with our bodies are warmer or colder than the skin.

The temperature sense also enables us to tell within rather narrow limits which of two bodies of the same kind is the warmer, but it does not enable us to judge of the temperature of bodies of different kinds. A piece of iron and a piece of wood may produce very different temperature sensations in our bodies when we know them to be actually of the same temperature.

The temperature sense, accordingly, gives us knowledge of the temperature of surrounding objects as related to our bodies, but it does not enable us to compare the temperatures of different bodies, or even to tell accurately how much warmer or colder another object is than our bodies.

Definition of Heat.—The name heat has been given to both the sensation and to the physical cause of the

sensation. In the study of Physics we define heat as *the physical condition which may give rise to the sensation of warmth in our bodies.*

Other Means of Recognizing Heat.—Heated bodies may be recognized by us in several other ways than by means of the temperature sense. We have seen that gases expand on heating, and that the amount of their expansion may be used as a measure of their change of temperature. We have also seen that solids may be changed to liquids and liquids to gases by simply increasing their temperatures. We also know that many bodies may be made luminous by heating, and that practically all of our appliances for artificial light depend upon the use of such luminous bodies.

SOURCES OF HEAT

Importance of Sun's Radiation.—The principal source of heat upon the earth is the radiation from the sun. The nature of this radiation can be better inferred after we have discussed more fully the physics of the Luminiferous Ether.

Chemical Sources of Heat.—Besides radiation, the most important source of heat is chemical action, especially combustion with oxygen. Many substances, including most of the materials of vegetable and animal bodies, will, when sufficiently heated, combine with oxygen to form new chemical compounds. The heat derived from this chemical combination may be many times as great as the heat required to start the combination in the first place, and this excess of heat may be made useful to us in many ways.

Mechanical Production of Heat.—Bodies may also be heated by percussion, friction, compression, and the

like. Thus a piece of iron may be made red hot by hammering it upon an anvil. A piece of wire held in the fingers and rapidly bent backwards and forwards soon becomes heated at the place of bending. Bodies are heated by rubbing one upon another, and savages sometimes build fires by the friction of one piece of dry wood upon another. Gases are heated by compression, so that in the process of inflating a bicycle tire the pump soon becomes sensibly warmed. In fact, when work is done upon a body in any way without increasing its kinetic or potential energy the body is usually heated.

NATURE OF HEAT

The Caloric Theory.—The modern theory of heat is based upon the discovery of definite relations between the expenditure of energy and the production of heat, and the disappearance of heat in the production of work. Before this discovery was made, heat was supposed to be an invisible, imponderable fluid, which could of itself pass from a hot to a cold body, and which could be forced from one body to another by percussion, compression, and the like. When a sufficient quantity of this fluid had penetrated a solid body, the body became a liquid, and a still greater quantity of the fluid mixed with the molecules of matter caused the body to assume the gaseous form. The name Caloric was given to this hypothetical fluid. Thus, water was supposed to consist of ice and caloric, steam of water and more caloric.

Count Rumford's Experiment.—The first experimental investigation which gave any accurate knowledge as to the true nature of heat was made by Count

Rumford in 1798. While engaged in the boring of brass cannon in the arsenal at Munich, Rumford was impressed by the great quantity of heat given off during the process. To determine, if possible, the source of this great quantity of heat, Rumford caused to be turned out a hollow brass cylinder about 25 centimeters long and 16 centimeters in external diameter in which he placed a blunt steel borer made to bear against the bottom with a pressure of about 10,000 pounds, and set it in rotation by means of horse-power. He found in this way that a great quantity of heat could be produced in the wearing away of a very small quantity of metal, and that there seemed to be no relation between the quantity of metal bored out and the quantity of heat produced. He found, however, that when his metal cylinder was placed in water and the borer kept in constant rotation the heat was generated at a uniform rate. He concluded that one horse working in turning his drill could in two and a half hours heat to the boiling-point 26.58 pounds of ice-cold water, or about 10 pounds an hour.

In reasoning upon the results of his experiments he says: "*It is hardly necessary to add that anything which an insulated body or system of bodies can continue to furnish without limitation can not possibly be a material substance; and it appears to me to be extremely difficult, if not quite impossible, to form any distinct idea of anything capable of being excited and communicated in the manner the heat was excited and communicated in these experiments, except it be Motion.*"

Davy's Experiments.—Following Rumford's experiment, Sir Humphry Davy succeeded in melting two pieces of ice by friction between their surfaces in a

vacuum at a temperature lower than the freezing-point of water, showing conclusively that the heat could not have been communicated from surrounding bodies, and must have come from the rubbing together of the ice surfaces. Rumford and Davy both believed heat to be due to the motion of the small particles or molecules of the hot body, and that when heat was produced by friction, percussion, and the like, the motion of the larger masses was transformed into the motion of the smaller particles. Accordingly, the physicists of that period undertook to determine experimentally the relation between the amount of motion destroyed and the amount of heat produced. This proved a very difficult problem. Since the time of Newton momentum had been taken to represent the measure of the quantity of motion of a moving body, and physicists naturally looked for a quantitative relation between the loss of momentum and the gain of heat. No such relation was found to exist. Energy, as a physical quantity, had not yet been discovered, and the relation between work and energy was consequently unknown.

Carnot's Theory.—Twenty-five years after Rumford's experiment, Sadi Carnot, in France, made many important investigations regarding the working conditions of steam-engines. At this time the steam-engine had been in use about fifty years, but apparently no one had thought of any relation between the work done by an engine and the heat lost by the steam during its production. Carnot made the observation that the steam was cooled more in driving the piston against an external pressure than when no work was done by the piston, so that much more heat was given up in the condensation of the steam when it was simply

blown through the cylinder than when it was compelled to drive the piston against external pressure. He accordingly concluded that some relation must exist between the quantity of heat lost by the steam in the cylinder and the amount of work done in the same time by the expansion of the steam.

The results of his reasoning on the question were summed up in some notes made by him but not published until after his death. He says, "*Heat is simply motive power, or rather motion which has changed form. It is a movement among the particles of bodies. Whenever there is a destruction of motive power, there is at the same time production of heat in quantity exactly proportional to the quantity of motive power destroyed. Reciprocally, whenever there is destruction of heat there is production of motive power.*

"*We can then establish the general proposition that motive power is in quantity invariable in nature—that it is, correctly speaking, never either produced or destroyed. It is true that it changes form—that is, it produces sometimes one sort of motion, sometimes another, but it is never annihilated.*"

Joule's Determination.—Carnot never succeeded in proving experimentally the relation between heat and what he called motive power, or the power to do work. This experimental proof was finally given by Dr. J. P. Joule, of Manchester, England. Dr. Joule began his experimental investigation of the subject in 1840, and worked at the problem for ten years before publishing his final conclusions. He found that a given quantity of work measured in foot-pounds could always be made to produce the same quantity of heat, and he concluded as the result of all of his experiments that 773.64 foot-

pounds of work when changed into heat would raise the temperature one pound of water by one degree Fahrenheit.

The Conservation of Energy.—In most of Joule's experiments the work was performed by weights actually falling under the influence of gravitation and by their energy turning paddle-wheels in water or rubbing together iron plates in water or mercury. The energy of the falling weight was thus transformed into heat by means of friction. Many experimenters have since worked upon the same problem and have found that the same amount of heat is produced whether the energy is transformed by means of friction, percussion, the electric current, or any other process. Carnot's conclusion has accordingly been experimentally established, and it is now believed that the total energy of the physical universe is a quantity which can neither be increased nor diminished by any known process. This theory is called the doctrine of the Conservation of Energy. Heat is only one of the forms in which energy may be manifested. We shall see later that other forms of energy, as the electric current, the potential energy of electric charges, and the energy of Ether vibrations may all be transformed into heat or mechanical energy and their quantities, like the calorie,* have their definite mechanical equivalents.

The Mechanical Theory of Heat.—To understand how the energy of a moving body may be changed into heat it will be necessary to recall some of the principles of the kinetic gas theory. In our discussion of the relation of gas pressure to molecular velocities (page 95), we saw that according to our theory the pressure

* For definition of the calorie see page 183.

of a gas confined to a constant volume must increase as the square of the average velocity of its molecules increases. We express this mathematically by saying that when the volume is constant the pressure varies as the square of the molecular velocity, or $p \propto v^2$. The product pv must also vary as v^2, and since an increase of v means a corresponding decrease of p, this will be true whether the volume is constant or not; hence we may write as before $pv \propto v^2$.

The kinetic energy of a moving molecule also varies as the square of its velocity, and the *average* kinetic energy of all the molecules in the gas varies as the square of their *average* velocity, hence we may write $E \propto v^2$, where E represents the average kinetic energy of the gas molecules.

Since $pv \propto v^2$ and $E \propto v^2$, $pv \propto E$.

The temperature of a gas measured on the absolute scale varies as the volume when the pressure is constant, or varies as the pressure when the volume is constant; hence $T \propto pv$.

We can accordingly write $T \propto E$, which means that the temperature of a gas measured on the absolute scale (see page 81) varies as the average kinetic energy of its molecules varies.

We have already seen that work done upon a body may increase either its kinetic energy or its potential energy. In the case of a gas, any increase of molecular kinetic energy will increase the temperature of the gas. *That which we call heat is, in a gas, only the kinetic energy of its moving molecules.* When these molecules strike upon the skin to which the temperature nerves are distributed they produce the sensation of warmth. When they strike upon the walls of their

containing vessels they give a part of their kinetic energy to the molecules of the walls, and the temperature of the gas molecules is lowered while the temperature of the molecules of the solid is raised.

We have seen that the average distance between the molecules of a gas is so great that they rebound from each impact to a distance greater than that through which cohesion can act, so that although two molecules are having their velocities accelerated while approaching each other and retarded while receding from each other, their total potential energy is neither increased nor diminished by the number of their collisions. Since their average distance is already greater than the distance through which cohesion can act, an increase in the volume of the gas will not increase their potential energy. In the case of a liquid the conditions are different. Any expansion of the liquid is opposed by cohesion, and hence work must be done upon the molecules to separate them.

Since liquids, as well as gases, expand on heating, any increase of the kinetic energy of their molecules is accompanied by an increase of volume. Any increase of volume of the liquid means that the average distance between its molecules is increased. This gives the molecules more potential energy than they had before and consequently requires the expenditure of kinetic energy, just as it requires the expenditure of kinetic energy to lift a heavy body against gravitation. Consequently if the same quantity of heat could be given to equal masses of any substance in the liquid and in the gaseous form, all the heat given to the gas would increase the kinetic energy of its molecules and accordingly increase its temperature; part of the heat given to

the liquid would increase the potential energy of its molecules, and the other part would raise its temperature. It requires about twice as much heat to raise the temperature of a gram of water one degree as it does to raise the temperature of a gram of steam one degree. Accordingly, about half the heat given to water is used up in increasing the potential energy of its molecules and the other half in increasing their kinetic energy.

EFFECTS OF HEAT

Expansion.—We are now prepared to consider intelligently some of the effects of heat in material bodies. We have already learned of its expansion effects in gases, and have seen how the change in gaseous volume or pressure may be used as a measure of the temperature change in the gas.

Liquids and solids also expand when heated, but their expansion is less than that of gases.

Heat Expansion of Water.

LABORATORY EXERCISE 48.—Place the overflow vessel used in Laboratory Exercise 40 on one pan of the platform balance and fill with cold water (ice water preferred), until some of the water overflows into a vessel placed beside the balance. Balance with weights on the other pan, and as soon as your balance is in equilibrium carefully take the temperature of the water with a thermometer. Record the weight of the water and its temperature. Empty the vessel and place it again upon the balance pan and pour it full of boiling water until some overflows. Record the weight and temperature as before.

Which expands more rapidly for a change of temperature, the water or the material of the overflow vessel? (N.B. If the vessel had been filled by a solid cylinder of its own material, the cylinder would have expanded just as fast as the outside vessel. For any solid cylinder may be conceived as made up of concentric cylinders of the thickness of the outside vessel, and if these did not expand and contract

together for a change of temperature, the outer layers would either separate from the inner ones or would be broken by the greater expansion of the inner ones.)

From the known weight of your overflow vessel, calculate how many grams of water it held at each of the measured temperatures. Supposing one cubic centimeter of the cold water used in your experiment to weigh one gram, what was the capacity in cubic centimeters of your overflow vessel at this temperature?

Your vessel being made of tinned iron, its expansion is the same as the cubical expansion of iron. The coefficient of cubical expansion of iron is .000036, that is, the volume of iron is increased by .000036 of itself for a change of temperature of one degree Centigrade. What was the capacity of your vessel at the higher temperature measured?

What is the weight of one cubic centimeter of water at this temperature?

What is the volume of one gram of water at this temperature?

What is the mean coefficient of cubical expansion of water between the temperatures measured by you? (The coefficient of expansion of water is very different at different temperatures. Thus between nine and ten degrees Centigrade it is .000077, while between eighty-nine and ninety degrees it is .00067.)

If a glass flask whose coefficient of cubical expansion is .000025 hold 1000 grams of water at the temperature of the cold water used in your experiment, how many grams of the hot water of your experiment will it hold?

If a glass bulb having the same expansion coefficient as the flask above mentioned weigh 250 grams in air and 150 grams in the cold water of your experiment, what will it weigh in the hot water?

Linear Expansion of Solids.

LABORATORY EXERCISE 49.*—Provide a piece of metal tubing of small bore and about one and a half meters long. The smallest size of gas-pipe will answer very well for the experiment. File a small notch in one side about twenty centimeters from the end, and make a scratch on the same side exactly one meter from the notch.

* The different forms of linear-expansion apparatus which can be purchased of dealers answer for this experiment.

Place two blocks or other supports about twenty centimeters high upon the table, upon one of which a flat strip of iron has been nailed and filed to a knife-edge to fit into

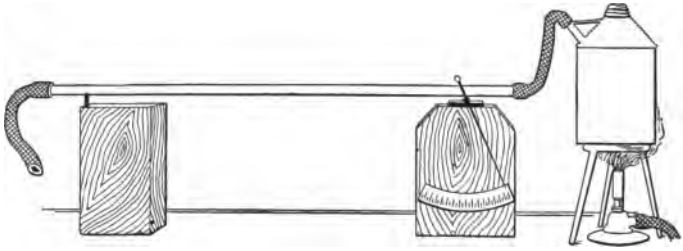


FIG. 45.

the notch in the tube. Upon the other support, at a distance of one meter from the knife-edge, a flat piece of glass should be fastened in a horizontal position with tacks. Cut off a piece of glass tubing two or three millimeters in diameter and four or five centimeters long, and, by means of sealing wax or shellac, fasten a long pointer, made of a straw or a glass thread which has been drawn out in a flame, to one end of the glass tube at right angles to the tube and about two centimeters from the larger end of the pointer. Cut the longer arm of the pointer so that its length from the surface of the glass tube will be some even number of times the diameter of the tube. Fifty times this diameter will be a convenient length. Stick a shot or a bit of wire to the short end of the pointer so that it will just balance the long end when the pointer is horizontal.

Place the metal tube upon the supports, letting the notch rest upon the knife-edge, and place the glass tube with the pointer attached upon the glass plate of the other support, and directly under the scratch on the metal tube. With a radius the length of the pointer from the surface of the glass tube draw an arc on a piece of cardboard or paper, and with a pair of dividers mark it off into a scale of millimeters. Attach this scale to the support so that the end of the pointer will just reach it, and so that the center of the arc is at the point where the glass tube rests upon the glass.

Connect one end of the metal tube by a piece of rubber tubing to a vessel in which water may be boiled. (A small

tin kerosene can may be used for a boiler. The top may be screwed down tightly, and the rubber tubing may be attached to the spout.*

Adjust the pointer so that it rests upon one division of the scale, and take the temperature of the metal tube, which should be the same as the temperature of the air in the room if the tube has not been recently handled. Boil the water in the attached vessel, and pass the steam through the metal tube and out through a piece of rubber tubing attached to the free end of the tube.

As the tube expands the pointer moves over the scale. When the expansion has ceased, read the position of the pointer, and calculate the amount of expansion of one meter of the tube. Observe that the glass tube and pointer form a lever, one of whose arms is the diameter of the tube and the other the length of the pointer.

Assuming the final temperature of the metal tube as 100° C., calculate the expansion of the tube in millimeters for one degree of temperature. By what fraction of its length does the tube expand for a change of temperature of one degree? This fraction is the expansion coefficient of the tube.

Calling l the length of your tube before expansion, l' its length after expansion, a the expansion coefficient, and t the temperature change, show that $l' = l(1 + at)$.

The expansion coefficient of steel is about .000012; what space should be left between the ends of steel rails 30 feet long in a climate where the temperature change may amount to 40° C.?

Relation between Linear and Cubical Expansion. —If we apply our equation to a cube the length of whose edge is l, we know that after heating the length of its edge will have changed from l to $l(1 + at) = (l + lat)$ and its volume will have changed from l^3 to $(l + lat)^3$. Cubing $(l + lat)$, and omitting all of the

* The boiler described as No. 80 in the list of apparatus published in the Harvard list of "Elementary Exercises in Physics" can be advantageously substituted for the tin can in this exercise and in Laboratory Exercise 57.

quantities which are multiplied by the square or the cube of a (a is never so great as .0001, and any ordinary number multiplied by a^2 or a^3 becomes very small), we have for the new volume $(l^3 + 3l^3 at)$ or $l^3(1 + 3at)$. In this equation $3a$ is the coefficient of cubical expansion which in our equation for gaseous expansion on page 81 we have expressed by b. Hence if b is the coefficient of cubical expansion and a the coefficient of linear expansion, we may without sensible error write $b = 3a$.

Coefficients of Linear Expansion.

	Expansion Coefficient.	1 meter heated through 50° C. expands
Aluminum	.000023	1.16 mm.
Brass	19	.95 "
Copper	17	.85 "
Ebonite	80	4.00 "
Glass	08	.40 "
Iron	12	.60 "
Lead	30	1.50 "
Magnesium	26	1.30 "
Nickel	13	.65 "
Platinum	09	.45 "
Silver	19	.95 "
Tin	23	1.15 "
Zinc	29	1.45 "
Wood, lengthwise—Oak	06	.30 "
Mahogany	04	.20 "
Fir	035	.17 "

Coefficients of Cubical Expansion.

Alcohol	.0010	Mercury	.00018
Ether	15	Petroleum	90
Ice	012		

PROBLEMS.—Why are platinum wires used for sealing into glass?

Why is wood better than metal for the pendulum rod of a clock?

How long must an iron bar be taken in order that its expansion for an increase of temperature may equal that of a bar of brass one meter long?

What is the volume at 300° C. of a piece of iron having a volume of 1 cubic centimeter at 0°?

If a piece of zinc have a density of 7 at 0°, what is its density at 100°?

CHANGE OF STATE

Melting.—We are all familiar with the phenomena of the change of bodies from the solid to the liquid and from the liquid to the gaseous forms when their temperatures are sufficiently increased.

The change from the solid to the liquid state by heating is called Melting or Fusion.

Conditions of Equilibrium of a Solid and its Liquid.—In Laboratory Exercise 44 we saw that sulphur may change directly from the solid to the liquid or from the liquid to the solid state without passing through any intermediate condition, while sealing wax softens or hardens gradually.

All crystalline substances which liquefy on heating change, like sulphur, from the solid to the liquid state without passing through any intermediate condition. In such cases the liquid and the unmelted solid are at the same temperature. Any increase of heat changes some of the solid into the liquid form without increasing its temperature, and any loss of heat causes some of the liquid to go into the solid form. The liquid and the unmelted solid may accordingly remain in contact with each other without changing the relative quantity of either so long as the mass neither receives nor gives off heat.

Melting Points.—The temperature at which a solid and its melted liquid may remain in equilibrium with

each other is called the Melting Point or Fusion Point of the substance. Amorphous substances, like sealing wax or glass, which change gradually from the solid to the liquid state, cannot be said to have any definite melting point.

Disappearance of Heat during Fusion.—Since the temperature of fusion of a crystalline substance remains constant until all the substance is melted, a large amount of heat may often be given to the substance without increasing its temperature. Before the relation between heat and energy was understood, this loss of heat could not be explained. The heat was supposed to still exist in the liquid in some form incapable of measurement, and was accordingly called Latent Heat. We now know that the molecules of a liquid have more potential energy of cohesion than the molecules of a solid, and that to give them this potential energy requires the expenditure of an equal quantity of kinetic energy. In the solid state the molecules are in their condition of most stable equilibrium, which means that their potential energy is less than in any other condition. Apparently they are held in definite positions with relation to each other and can only vibrate back and forth within certain limits. It is as if they were held together by attractions between definite points on the molecules, as magnets are held together by attractions between their poles. If two magnets are separated, keeping their attracting poles turned toward each other, work must be done upon them, and they must acquire potential energy. If instead of separating them they are rotated rapidly about axes perpendicular to the line joining them, their attraction for each other is also lessened and their potential energy increased,

for they are capable of doing work for the sake of getting back to their positions of rest. If the cohesion between molecules tends to bring the molecules to rest in definite positions relative to each other, then the potential energy between molecules may be increased by separating them, or by setting them in rapid rotation. In heating a body, some of the energy given to the body increases the energy of vibration of the molecules, and this can be observed in the expansion of the body and can accordingly be measured as temperature. Another part may increase the potential energy of the molecules by increasing their average distances from each other or by setting them in rotation. When a molecule escapes from a crystal surface into the liquid surrounding it, it acquires potential energy in one of these forms without acquiring any additional kinetic energy. Hence some of the heat used in melting bodies disappears as molecular kinetic energy and becomes molecular potential energy. In changing back from the liquid to the solid state, the potential energy of liquefaction again becomes kinetic, and must be given off to surrounding bodies if the process of solidification is to continue. Thus the freezing of one substance must result in the warming of some other substance. In our experiments on heat measurements we shall learn how to measure the quantity of heat made "latent" in the process of fusion.

Change of Volume in Melting.—Bodies which have a definite melting point usually show an abrupt change of volume on liquefaction. Most substances expand on melting, but there are many exceptions. Solid substances which float in their liquid at the melting point contract on melting. Ice is the most notable

example of this kind. Its volume contracts by nearly nine per cent of itself on melting. This fact is of great importance in the economy of nature. The ice which forms on streams and lakes in the winter covers the surface of the water and prevents the rapid loss of heat. If it settled to the bottom, the water in the colder regions of the earth would be entirely frozen in the winter.

Bismuth contracts about 2.3 per cent of its volume on melting, and the other common metals expand. Metals which expand on melting and contract on cooling are not well adapted for casting, as they do not take sharp impressions of the mold. Iron contracts only about one per cent on solidification. Copper contracts about seven per cent, and silver more than eleven per cent. These metals are accordingly not cast into coins, but the coins are stamped out of the solid metal.

Influence of Pressure upon the Melting Point.— Since the cohesion attraction is so great between the molecules of solids and liquids, any change in external pressure affects but slightly the melting point of solids. In general, substances which contract on melting have their melting point lowered by an increase of pressure, and substances which expand on melting have their melting point raised by an increase of pressure. The melting point of ice is lowered about .0075° C. for an increase of pressure of one atmosphere, or about one degree for a pressure of a ton to the square inch.

When ice is already at the melting point it may be liquefied by pressure. In pressing together small bits of melting ice or a mass of snow which is already at its melting point, the pressure may become great enough at the points of contact to cause some of the solid to

melt, and thus the separate particles may be molded into a solid mass. In this case, the additional potential energy required by the liquid particles is furnished by the work done in compressing the mass.

Energy Changes in Solution.—When a solid is changed to a liquid by dissolving it in another liquid, a quantity of kinetic energy is changed to potential energy, just as in the process of fusion, and the temperature of the solution is lowered by the loss of this kinetic energy. Frequently, however, a contraction of volume takes place in solution, and potential energy is lost and kinetic energy gained by this contraction. This gain of kinetic energy by contraction may be greater than the loss of kinetic energy by the liquefaction of the solid. Thus water is cooled by the solution of sodium sulphate, but is warmed by the solution of sodic hydrate.

Freezing Mixtures.—In some cases of solution the lowering of temperature is so great that the solution may be used as a freezing mixture. Sometimes two solids when mixed will combine to form a liquid solution, and the gain in potential energy of both substances causes a great decrease in their kinetic energy. Thus two parts by weight of ice and one of common salt form a liquid solution which has a freezing point far below that of water. In the preparation of this solution a great quantity of energy is changed from the kinetic to the potential form, and if the mixture cannot acquire heat from surrounding bodies its temperature falls as much as twenty degrees below zero Centigrade. Such a mixture of salt and ice is frequently used as a freezing mixture.

Vaporization.—The change from the solid or liquid

to the gaseous state is known as vaporization. Substances which vaporize readily are said to be volatile. We have already seen that liquids evaporate at ordinary temperatures, and that a certain vapor pressure, which was measured in Laboratory Exercise 30, is necessary to permanently maintain the liquid condition. This process of vaporization at the surface of a liquid we have called evaporation.

In Laboratory Exercise 37 we saw that the vapor pressure of a liquid increases as the temperature of the liquid increases, so that when the liquid boils its vapor pressure becomes as great as the atmospheric pressure.

Boiling Points.—The temperature at which the vapor pressure of a liquid becomes as great as the atmospheric pressure upon the liquid is called the Boiling Point of the liquid. Since the vapor pressure increases with the temperature, the greater the atmospheric pressure upon the surface of the liquid the hotter must the liquid be at its boiling point.

The vapor pressures of many liquids at different temperatures have been determined by a method similar to the one used in Laboratory Exercise 30, the difference being that the top of the Torricellian tube is surrounded by a vessel, which can be filled with water at any temperature desired, and the vapor pressure of the liquid at that temperature can be determined. The vapor pressure of water at zero Centigrade is 4.57 millimeters of mercury, or more than 6 grams to the square centimeter, and water will accordingly boil at its freezing point when the atmospheric pressure is reduced to this amount.

Lowering of Boiling Point by Decrease of Pressure. LABORATORY EXERCISE 50. — Select a round-bottomed

Florence flask with a strong neck, fill it about one third full of water, and heat it over a flame until the water has boiled

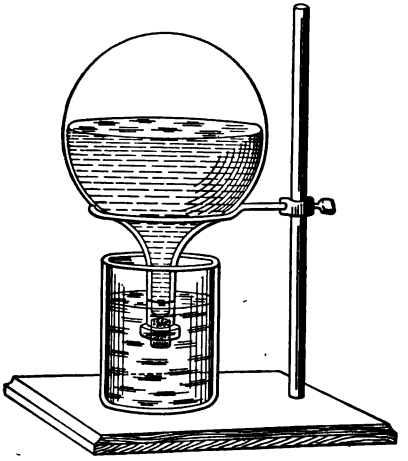


FIG. 46.

rapidly for some time to drive out the air from the flask. Close the flask with an air-tight stopper (a rubber stopper is best for this purpose), and support it neck downwards upon a ring. The flask will then contain only water and water vapor. Place the neck of the flask in water so that no air may enter, and cool the flask above the water rapidly by letting cold water drip upon it. This will condense some of the water vapor upon the walls of the flask, and will accordingly lower the vapor pressure upon the contained water. This will cause the water to boil. Continue in this way to condense the vapor and to cause the water to boil as long as possible. Then withdraw the stopper and take the temperature of the water.

The accompanying curve shows the vapor pressure of water in centimeters of mercury at different temperatures as determined by Regnault. Since water will boil when its vapor pressure equals the external gas pressure upon it, this curve will enable you to deter-

mine the boiling point of water at different barometric pressures.

PROBLEMS.—Taking the temperature of water in the flask as determined in the preceding experiment, what was the lowest vapor pressure which you were able to produce by cooling the flask?

Water within the receiver of an air-pump is seen to boil

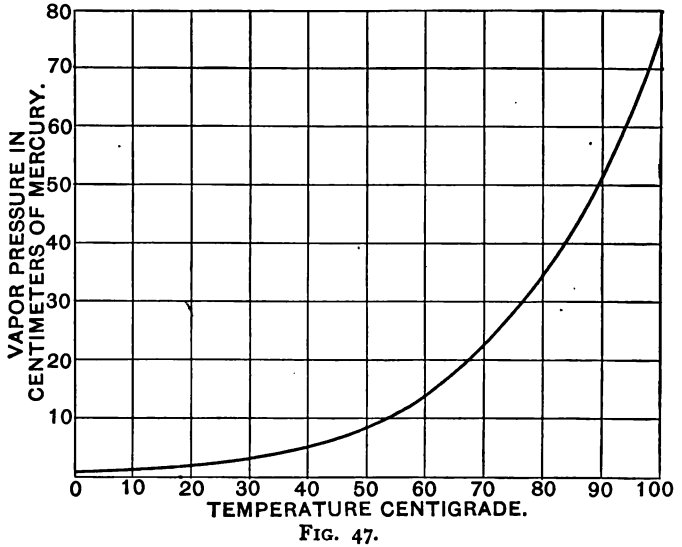


FIG. 47.

at 60° C.; what is the atmospheric pressure within the receiver?

At what temperature will water boil on the top of a mountain where the barometer stands 50 centimeters high?

What is the barometric height on a mountain where water boils at 90° C.?

It will be seen from the curve that the vapor pressure does not increase uniformly with the increase of temperature. In the neighborhood of 100° C. this increase may be taken as about 2.7 centimeters for a change of temperature of one degree. The change in the boiling point of water is accordingly about 0°.37 for a change of one centimeter in the barometric height.

What is the barometric height when the boiling point of water is 99°.26 ?

Boiling Points of Solutions.—When a substance dissolves in water it is an indication that the cohesion between its molecules and the water molecules is greater than between the molecules of water or the molecules of the dissolved substance. Since evaporation is opposed by cohesion, the vapor pressures of the substances entering into the solution will both be lowered by the solution. If the dissolved substance be a solid or a liquid having a lower vapor pressure than water, the vapor pressure of its aqueous solution will be lower and the boiling point higher than for pure water. If the dissolved substance have a higher vapor pressure than water, the vapor pressure of the solution will be less than that of the more volatile substance, but may be greater or less than that of water.

Distillation.—Two volatile liquids in solution accordingly each have their own vapor pressure in the solution, but this vapor pressure is less than for the substances in the pure state. If the temperature be sufficiently raised, one of the liquids will boil before the other, and when the boiling point of this liquid is reached the temperature cannot be raised until some of the liquid has been removed by boiling. At this temperature, the vapor of the more volatile liquid escapes more rapidly than the vapor of the other liquid, and when the vapor of the boiling solution is again condensed into a liquid it will contain a much larger percentage of the more volatile constituent than did the original solution. By repeating the process, a still more concentrated solution of the more volatile con-

stituent can be prepared. It is by this process that alcohol is usually separated from water.

If one constituent of the solution have a very low vapor pressure, the other constituent may be almost completely separated from it by boiling. The process of separating the constituents of a solution by boiling

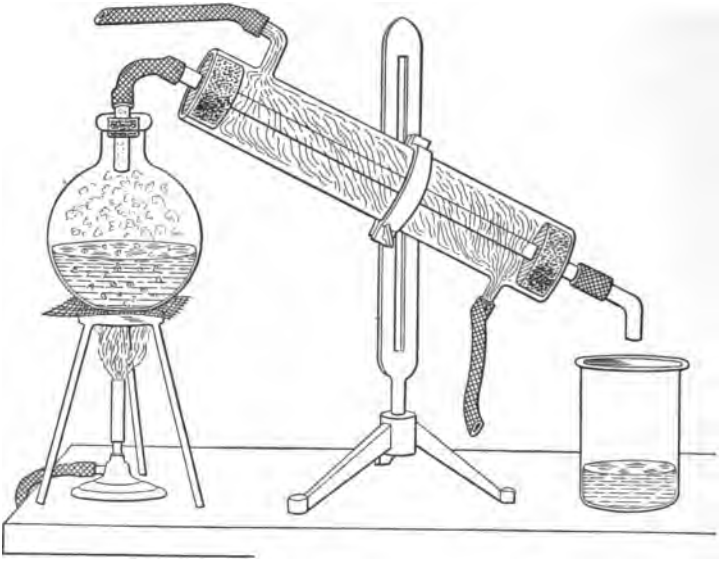


FIG. 48.

off the more volatile one and condensing it again in a cold vessel is known as Distillation. When both of the constituents are volatile and the separation is only partial, as in the case of alcohol and water, the process is known as fractional distillation. The method of distillation in common use is to pass the vapor from the boiling liquid through a long tube cooled in water and to catch the condensed liquid in another vessel. One arrangement of apparatus commonly used in the labora-

tory is shown in Fig. 48. The vessel in which the liquid is boiled is called the still, and the arrangement for liquefying the vapor is called the condenser.

Relation of Boiling Point of Solution to Concentration.

LABORATORY EXERCISE 51.—Weigh out about 10 grams of common salt and dissolve in about 100 cubic centimeters of water. Boil the solution in a beaker or flask and note the temperature of the boiling point. Let the boiling continue until the water is mostly boiled off and salt begins to precipitate in the solution, taking the temperature of the boiling point at occasional intervals. When there is not sufficient water left to dissolve all the salt, place the vessel in a sand or water bath and let the evaporation continue until the water has disappeared.

Does most of the salt remain? How does the increase in the concentration of the solution affect its boiling point?

Why is rain water fresh, while the water of the ocean is salt?

Which will boil at the lower temperature, rain water or sea water?

Sublimation.—Some solids when heated pass at once from the solid to the gaseous state without passing through any intermediate liquid state. This process is called sublimation. Thus, if a crystal of iodine be put in a test tube or a glass tube sealed at one end and warmed gently over a flame, the iodine will at once change into a violet vapor which will condense again into crystals on the cold sides of the tube.

CONDENSATION OF ATMOSPHERIC VAPOR

Aqueous Vapor in the Atmosphere.—We know that water is constantly evaporating into the air, and that the atmosphere must at all times contain considerable quantities of water vapor. We have also seen that the quantity of water vapor which can exist above a water

surface before condensation will begin depends upon the temperature. The curve on page 158 shows the maximum vapor pressure which can exist in contact with a water surface at different temperatures. Lowering the temperature or decreasing the space in which the water vapor is confined causes some of it to condense upon the water surface or upon the surface of the containing vessel.

Formation of Dew.—When the atmosphere is sufficiently cooled its vapor will likewise condense upon solid or liquid surfaces in contact with the air. When atmospheric vapor condenses upon bodies on the surface of the earth it is called Dew.

The Dew Point.—The temperature just below which dew will begin to condense from the atmosphere is called the Dew Point. When the temperature of the air has been cooled to the dew point the air is said to be saturated with vapor, and the dew point is sometimes called the temperature of saturation. This term is misleading. The air is not, and cannot become, saturated with vapor, for the air does not absorb moisture. Evaporation takes place into the air just as it does into a vacuum, and the dew point is not affected by the presence of the air. When the surfaces of bodies exposed to the water vapor in the air are sufficiently cooled, the water molecules which strike them lose so much of their kinetic energy that they are held to the surface by cohesion instead of rebounding from it as they would do if their kinetic energy were greater. When these same surfaces are sufficiently heated the water will evaporate from them. The temperature at which as much water is condensed upon the surface as is evaporated from it in the same time is the tempera-

ture of the dew point. Air in a closed receiver containing water is always at its dew point after standing for a short time.

Determination of Dew Point.

LABORATORY EXERCISE 52.—Fill a brightly polished metal vessel (a tin cup or tin can will do as well as anything) about half full of water at the room temperature. Cool this water gradually by pouring in ice water from another vessel, stirring the water all the time, until a trace of moisture can be seen on the outside of the vessel. Take the temperature of the water with a thermometer. Allow the vessel of water to stand and become warmer until the moisture disappears, and take the temperature again. Add a little cold water and note again the temperatures at which the moisture appears and disappears, bringing these two temperatures as closely together as possible. To do this, the faintest trace of moisture on the vessel must be observed. This can best be done by noting the image of some object reflected from the brightly polished surface. Do not get near enough the vessel to allow your breath to condense upon it. Take the mean of the temperatures of appearance and disappearance of the moisture as the dew point.

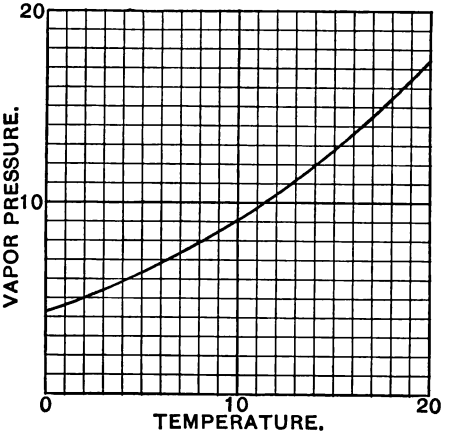


FIG. 49.

To what temperature must the air in your laboratory fall before dew will condense upon objects in the room?

The curve previously referred to on page 158 shows the maximum vapor pressure which water can exert at different temperatures. Since this maximum pressure is exerted when

as much water is condensed as is evaporated in the same time, which is the condition at the temperature of the dew point, the curve shows the temperature of the dew point for any vapor pressure given. The accompanying curve, Fig. 49, shows this same pressure in millimeters of mercury for temperatures from 0° to 20° C.

What was the barometric pressure of the water vapor in the air at the time of your experiment?

What part of the observed barometric height is due to dry air, and what part to water vapor?

What is the dew point of the atmosphere when its water vapor exerts a barometric pressure of 10 millimeters of mercury?

The Hygrometer.—Any instrument used for measuring the quantity of aqueous vapor in the air is called a Hygrometer. The instrument by means of which you have determined the dew point is accordingly a hygrometer.

Formation of Frost.—When the water vapor of the air is condensed upon a surface which is cooled below the freezing point of water, the surface becomes covered with a coating of ice crystals called hoar frost. This may be shown by allowing the moisture to condense upon the surface of a vessel filled with a freezing mixture, as broken ice and salt. The crystalline form of ice is very noticeable in hoar frost, especially upon window panes.

Condensation within the Atmosphere.—The air at all times contains large numbers of small dust particles which have been carried up by the winds. These particles, though too small to be seen with the naked eye, have surfaces upon which condensation takes place as upon larger bodies. Each particle, when cooled below the dew point of the air, becomes covered with condensed moisture. When the particles with their

water coating become large enough to be visible to the eye they form a fog or cloud. If the moisture continues to condense upon them, they soon become heavy enough to fall rapidly, and are then called rain drops. Rain is accordingly nothing but dew which has condensed upon the floating particles in the atmosphere. Air can be artificially freed from dust particles so that no fog is formed in it when it is cooled far below its dew point.*

If the floating particles in the air are cooled below the freezing point of water, they become the centers of crystallization for the ice molecules which come in contact with their surfaces. Snow is accordingly hoar frost deposited upon atmospheric dust particles.

Formation of Clouds.—The atmosphere is warmest near the surface of the earth and cools rapidly as it ascends. When it is cooled below its dew point condensation takes place upon its dust particles and a cloud is formed. If the water drops formed upon the dust particles are small, they will sink toward the earth very slowly. When they have settled into the warmer air below them the water evaporates from their surfaces and they disappear. The bottom of a cloud accordingly represents the height above the earth at which the air is cooled to its dew point.

When the air near the earth's surface is cooled below its dew point, the clouds settle to the earth and we call them fog. Since the air very near the earth contains many more dust particles than the air at greater heights, the drops of water formed in a fog are usually

* Recent experiments have shown that the chemical atoms of gases may be broken up into parts which carry electrical charges, and that these electrified parts of atoms, called Electrons, may also serve as nuclei for the condensation of the water vapor of the atmosphere.

more numerous than in a cloud. In cities where the air is filled with particles of dust from chimneys and other sources, fogs often become very dense.

PROBLEMS.—What is the barometric pressure of the water vapor in the air on a foggy day when the temperature is 15° C.?

Water vapor is about .6 as heavy as air at the same pressure and temperature; calculate the weight of water vapor in your laboratory at the time of your determination of the dew point.

CRITICAL TEMPERATURES AND PRESSURES

Critical Temperatures.—We have seen that the vapor pressure of water rises as the temperature rises. At 100° C. it is equivalent to 76 centimeters of mercury. At 200° C. it is equivalent to 1169 centimeters of mercury, more than 15 atmospheres. At a temperature of 365° C. no known pressure can condense water vapor into a liquid. When heated to this temperature in a closed vessel no surface of separation can be observed between the water and the steam.

The temperature at which the whole of a liquid changes into vapor under the greatest possible pressure that can be applied to it is called the Critical Temperature of the liquid. At this temperature the kinetic energy of the molecules becomes so great that they will rebound from each other after each impact notwithstanding the cohesion attraction. The critical temperature of water is accordingly 365° C.

Liquefaction of Gases.—When a liquid is heated above its critical temperature it becomes a permanent gas, and cannot be liquefied by pressure. The gases of the atmosphere are at all times above their critical temperature and cannot be liquefied until they are

cooled far below atmospheric temperatures. When their temperatures are sufficiently lowered, all gases may be liquefied by pressure.

After a gas has been liquefied the external pressure may be reduced and the liquefied gas will boil away at a constant temperature which is always lower than its critical temperature. Thus air at a temperature of — 140° C. and under a pressure of 39 atmospheres is condensed to a liquid which at atmospheric pressure will boil at a temperature of — 191° C. Hydrogen at a temperature of — 223° C. and a pressure of 15 atmospheres is condensed to a liquid which boils at — 238°.5 C., and which freezes to a solid mass at about — 256° C.

Table of Critical Constants of Gases.—The following table shows the critical temperatures, the pressures necessary to liquefy the gases at these temperatures (called Critical Pressures), and the boiling points of a few of the common gases.

Gas.	Crit. Temperature.		Crit. Pressure.	Boiling Point.	
	C.	Abs.		C.	Abs.
Hydrogen	— 223°	50°	15 at.	— 238°.5	34°.5
Nitrogen	— 146°	127°	35 "	— 194°.5	78°.5
Oxygen	— 119°	154°	51 "	— 181°.5	91°.5
Air	— 140°	133°	39 "	— 191°	82°
Carbon dioxide	31°	304°	73 "	— 78°.2	194°.8

Lowest Known Temperature.—The lowest temperature yet reached has been produced by allowing liquefied hydrogen to boil at a low pressure, about 35 millimeters of mercury. The temperature which has been reached in this way is believed to be as low as

— 259° C., or only 14° above the absolute zero. It is by means of the low temperature produced in this way that liquid hydrogen may be frozen.

ENERGY CHANGES IN VAPORIZATION

Disappearance of Heat during Vaporization.—We have already learned that the molecules of any substance have more potential energy in the gaseous than in the liquid form. It must accordingly require an expenditure of kinetic energy to change a substance from the liquid to the gaseous form. The kinetic energy thus expended is known as the Latent Heat of Vaporization.

Cooling of Ether by Evaporation.

LABORATORY EXERCISE 53.—Provide two test tubes, one of which will slide easily within the other. Pour a little water into the large tube and push the smaller one down into the water to the bottom of the larger. The water will rise between the tubes and overflow, and the space between them will be filled with water.

Pour the inner tube about half full of ether, taking care that none gets into the water between the tubes. Through a glass tube reaching nearly to the bottom of the ether blow air from a foot bellows or the lungs so that it will rise in large bubbles through the ether. This will cause rapid evaporation of the ether, and some of the heat used up in increasing the potential energy of the ether molecules will be taken from the water surrounding the tube. If the outer tube be held so that it does not receive heat from the hand or other body, the water between the tubes may be frozen.

The experiment may be modified by evaporating ether rapidly from a watch crystal set upon a drop of water on a board.

Drop a little ether on the hand and note the cooling sensation.

Wrap a thin cloth about a thermometer bulb and moisten it with ether which has been standing in the room until its

temperature is about that of the air in the room. What change do you observe in the thermometer?

Tie a thin piece of cloth about a thermometer bulb, and dip one end of it in water at the room temperature and let the water rise by capillarity and evaporate from around the thermometer bulb. Note any temperature change that may occur in the thermometer.

Would the water evaporate faster on dry or on a moist day? Would the difference in temperature between a wet-bulb and a dry-bulb thermometer be greater on a dry or on a moist day?

The Psychrometer.—A wet- and a dry-bulb thermometer mounted side by side form an instrument much used for estimating the humidity of the air. This instrument is called a psychrometer. It is impossible to calculate theoretically the humidity of the air from this instrument, but, by a long series of observations upon it in connection with the dew-point determinations by other means, hygrometer tables have been made which give very approximately the amount of aqueous vapor in the air from the readings of this instrument.

DISTRIBUTION OF HEAT

CONDUCTION

Definition.—Heat is conveyed from one body to another in several different ways. When heat is transferred from one particle to another through a body, the process is called conduction.

Conduction in Solids.—Solids differ greatly in their capacities for conducting heat. Accurate measurement of the amount of heat carried by a body is a difficult process, but it is easy to show qualitatively that one body may conduct heat better than another. If wires

of copper and iron of the same size be held in the hand while an end of each is heated red hot in a flame, the copper wire will feel hot at a greater distance from the flame than the iron wire. A glass rod may be held in the fingers very close to the flame while its end is melted. A lighted match may be held until the flame has burned very near to the fingers without any perceptible heating of the wood.

This difference in the heat conductivity of bodies causes them to seem of very different temperatures when all are practically at the temperature of the surrounding air. We judge of the temperature of bodies when in contact with our skin by the rate at which heat is gained or lost by the skin. A very cold body which is a poor conductor of heat may feel warmer to our touch than a body less cold which is a better conductor of heat. In the former the surface in contact with the hand is very soon warmed, while in the latter the heat is conducted away nearly as rapidly as it is received.

The nature of heat conduction in solids is not at all understood. If the vibrating molecules actually strike against each other and divide their energy in this way, it is thought that conduction should be a more rapid process than it is. Then we have seen reasons for believing that in crystalline bodies, at least, the molecules are spaced at definite distances from each other and accordingly should not strike against each other in their vibrations. In this case, the vibrations of one molecule could disturb another one only by setting up vibrations in some medium extending between them.

Law of Conductivity.—The quantity of heat which will pass through a conductor, say a metal plate, in a

given time is proportional to the difference of temperature of the two faces of the conductor and to the area of the cross-section of the conductor, and is inversely proportional to the thickness of the plate.

Thus if Q represent the quantity passing through the conductor, T_1 the temperature of one face, T_2 the temperature of the other face, e the thickness of the plate, and A the area of its cross-section,

$$Q = k\frac{T_1 - T_2}{e}A,$$

where k is a constant factor for the given material but is different for different materials, and is called the coefficient of conductivity.

Conduction in Liquids.—If a piece of ice be held in the bottom of a test tube of water by means of a weight of lead or a piece of wire, and the test tube be inclined over a flame so that it is heated about the middle of the tube, the water may be boiled without melting the ice below it. This shows that water is a very poor conductor of heat. The same may be said of all liquids except mercury.

Conduction in Gases.—The determination of the heat conductivity of gases is a matter of extreme difficulty, as it is impossible to tell how much of the heat has been carried by conduction proper, as in solids, and what part by gas currents. A hot body will cool more rapidly in hydrogen than in air, but it is impossible to prevent diffusion currents in the gases, while such currents do not exist in true conduction in solids.

Table of Conductivities.—The following table will give the conductivities of various substances as referred to the conductivity of silver taken as 100:

Solids.		Fluids.	
Silver	100	Mercury	1.35
Copper	73.6	Water	.140
Gold	53.2	Glycerine	.084
Tin	15.2	Alcohol	.052
Iron	11.9	Ether	.046
Lead	8.5	Olive oil	.045
Brass	27.3	Chloroform	.041
German silver	6.3	Air	.0066
Ice	.21	Hydrogen	.0468
Glass	.046	Carbon dioxide	.0039
Hard rubber	.024	Illuminating gas	.0176

Through what thickness of silver will heat flow as rapidly as through 1 millimeter of hard rubber?

On account of its low conductivity, a layer of ice over water is a great protection from further freezing.

CONVECTION

Formation of Currents by Gravitation.—If liquids and gases were removed from the action of gravitation, their principal method of heat distribution would be by means of diffusion. The effect of gravitation is to set up currents in the heated fluids and in this way to greatly hasten the diffusion process.

We have seen that fluids are expanded by heat, and that on account of their increase in volume the heated parts have their density decreased and are pushed up by the colder parts. A liquid or a gas heated at the bottom will accordingly have ascending and descending currents set up in it, and by means of these the cooler parts of the fluid will constantly be brought into contact with the source of heat.

Thus in the experiment with the ice and the boiling water in the test tube it is necessary to heat the water

above the ice, as otherwise the water cannot be heated until after the ice is melted. The same conditions exist in the air. The hand held above a heated iron will feel the heat much more plainly than if held below it.

The ascending and descending currents set up by gravitation in a heated liquid or gas are called Convection Currents. The distribution of heat by means of these currents is called Convection.

Convection Currents in Water.

LABORATORY EXERCISE 54.—Fill a small beaker with clear water and allow it to stand protected from direct sunlight until the water has come to rest, say for five minutes. Dip a pen into aniline ink, as violet or green ink, and touch it to the surface of the water, leaving colored ink on the surface. This ink will diffuse into the water very slowly, but it will be carried about by any currents in the water. If the water is colder than the room, there will be ascending currents around the outside of the vessel and descending currents in the center, and these will be shown by the movements of the colored water. If the water is warmer than the air, the descending currents will be around the outside of the vessel. If one side of the vessel receive more heat than the side opposite, there will be ascending currents on the warmer side. The best currents for experimentation are slender ones, such as are shown in Fig. 50. If these do not appear on first trial, repeat with another beaker of water.

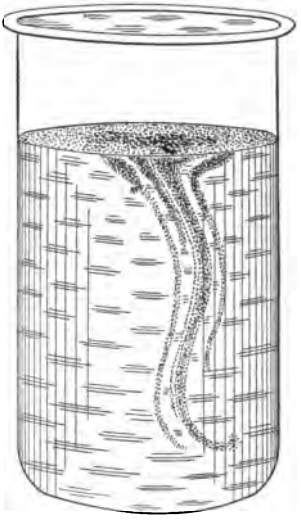


FIG. 50.

After the currents are plainly indicated by the colored ink columns, hold the warm finger

against the side of the vessel near a slender descending current and explain the movement produced in the current. Do the same near an ascending current. Light a match and hold against one side of the beaker.

Place a beaker of water where the sun shines upon one side of it, and after it has stood for a few minutes touch the surface with the ink and account for the currents produced.

Fill a test tube with cold water and stand it inclined at an angle. After it has stood for a few minutes, touch the ink to the water and explain the currents.

Importance of Convection Currents in Nature.—Convection currents play a very important part in the economy of nature. The atmospheric and oceanic circulations are entirely carried on by them. With the exception of the tides, all the energy of wind or ocean currents is derived from convection currents.

Heating and Ventilation of Houses.—In warming and ventilating our houses we make frequent use of convection currents. We remove the smoke and the gaseous products of combustion from our fires by building chimneys in which a column of air can become heated without diffusing into the surrounding atmosphere. This column of air expands and becomes lighter than a column of the surrounding air of the same height, consequently it is pushed upward by the buoyant force of the colder air. The taller the hot-air column, the more difference there is between its weight and the weight of a column of the surrounding air of the same height, hence the greater the unbalanced upward pressure against it, and the greater the draught in the chimney.

In the hot-air furnace used for warming buildings, the air is heated in a chamber above the fire. Pipes lead upward from this chamber to the rooms where the heat is wanted, and another pipe runs downward and

outward to the cold air outside the building. The constant pressure exerted by the cold outside air pushes the lighter air in the pipes upward into the rooms and through flues or other openings in the walls into the outside air again.

In the warm-water heaters the conditions are similar except that the cold water is taken from a reservoir in the top of the house, from which it flows downward into the heating apparatus and pushes up the columns of warm water which go through the radiators in the rooms and then discharge into the cold-water reservoir. The warm- and cold-water columns are of the same height, and since the water is continually lighter in one column than in the other equilibrium is impossible.

Questions on Convection.

Why can you not produce convection currents in a liquid by heating it at the top?

Why is it easier to ventilate a room by means of two small openings than by one large one?

If a door between a warm and a cold room stand open a few inches and a lighted candle be moved upward and downward in front of the opening, the flame will be blown from the warm room toward the cold room at the top of the door, and from the cold room toward the warm room at the bottom. Why?

If a lamp chimney be set over a burning candle so that no air can enter at the bottom, the candle will go out. Why?

If a partition made by a little piece of cardboard be put in the top of the chimney, the candle will continue to burn. Explain.

Why will a match burn faster when the lighted end is held downward than when it is held upward?

RADIATION

Transference of Energy through a Vacuum.—Heat may be transferred from a warm to a cold body in a vacuum. Here the process can be neither conduction nor convection. In conduction the heat is passed from one particle to another of a material body, while in convection the heat is carried by the movements of heated material particles. If we define heat as on page 144 as the kinetic energy of moving molecules, then there can be no heat in a vacuum; nevertheless molecules may lose their kinetic energy in a vacuum, while other molecules may gain kinetic energy from the vacuum. We accordingly conclude that what we call a vacuum is filled with a medium which is not apparent to any of our senses but which is capable of transmitting energy. This medium is known as the Luminiferous Ether, because it was first recognized by the part which it takes in the phenomenon of light. The energy absorbed by the luminiferous ether is supposed to exist in some form of vibration, and is called Radiant Energy.

Definition of Radiation.—The process by which radiant energy is transmitted in the Ether is called Radiation.

Mutual Transformation of Heat and Radiant Energy.—The process of radiation is most conveniently studied in connection with the subject of light. Some of the conditions under which heat is transformed into radiant energy and radiant energy into heat may be noted here.

All of the energy received from the sun comes to us by means of radiation. When this energy is transformed into heat it is said to be absorbed.

Absorption of Radiant Energy.

LABORATORY EXERCISE 55.—Place a piece of transparent glass and a piece of smoked glass in the sunlight with their surfaces inclined at the same angle to the sun's rays, and decide by the sense of touch which is heated the more rapidly.

Take two small flasks of the same size, smoke the outside of one over a candle flame, fill both with cold water at the same temperature, insert thermometers in the corks of both and set them in the sunlight. Which absorbs heat the more rapidly?

Fill them both with hot water at the same temperature and set them in the shade. Which cools the more rapidly?

Selective Absorption.—Substances frequently allow one sort of radiant energy to pass through them, but absorb radiant energy of another sort. Thus glass allows the radiant energy from the sun to pass through it, but reflects and absorbs the radiant energy from a hot stove. The air allows the radiant energy of the sun to pass through it with little loss, but absorbs the radiant energy of the heated earth. This is especially true of the water vapor in the air. It is for this reason that the atmosphere is heated at the bottom instead of at the top. If the atmosphere were absent from the earth, the difference between night and day temperature would be much greater than it is. In very dry regions where the air contains but little water vapor the temperature extremes are much greater than in moist regions.

Reflection of Radiant Energy.

LABORATORY EXERCISE 56.—With a concave mirror reflect the sunlight upon a piece of paper. Move the paper until the spot of light reflected from the mirror is as small as possible and note if there is any heating effect upon the paper. Can radiant energy be reflected? Does radiant energy pass through glass?

Relation between Radiation and Absorption.—We have seen from the above experiments that bodies differ in their capacity for taking up radiant energy and for giving off their heat energy in the form of radiation. Apparently if the molecules of a body are easily set in vibration by the Ether, their vibrations are likewise rapidly damped by the Ether, so that bodies which readily absorb radiant energy also readily lose their own heat energy by radiation.

HEAT MEASUREMENTS

Two Kinds of Measurements.—Two kinds of heat measurements are possible. We may measure the intensity of heat in a body, or we may measure the total quantity of heat energy in the body. The former we call the temperature of the body, and the latter the heat quantity of the body.

We have seen that temperature is the measure of the average kinetic energy of the molecules of a body. If a body consisting of only a few molecules contains a large quantity of heat energy, then the average kinetic energy of its molecules must be great and its temperature is high. The same quantity of heat given to another body consisting of more molecules will not raise its temperature so high.

THERMOMETRY

Definition.—The measurement of temperature is called Thermometry. Temperature measurements may be based upon any property of bodies which varies continuously with temperature changes. We have seen that the expansion of gases is such a property, and our absolute scale of temperature is based upon gas expansion.

Construction of Thermometers.—An instrument for measuring temperature changes by means of the expansion of bodies is called a thermometer. The expanding substance used is generally a gas or a liquid, and must be enclosed in a solid. The observed expansion is accordingly the difference in the expansion of the fluid and of its containing vessel.

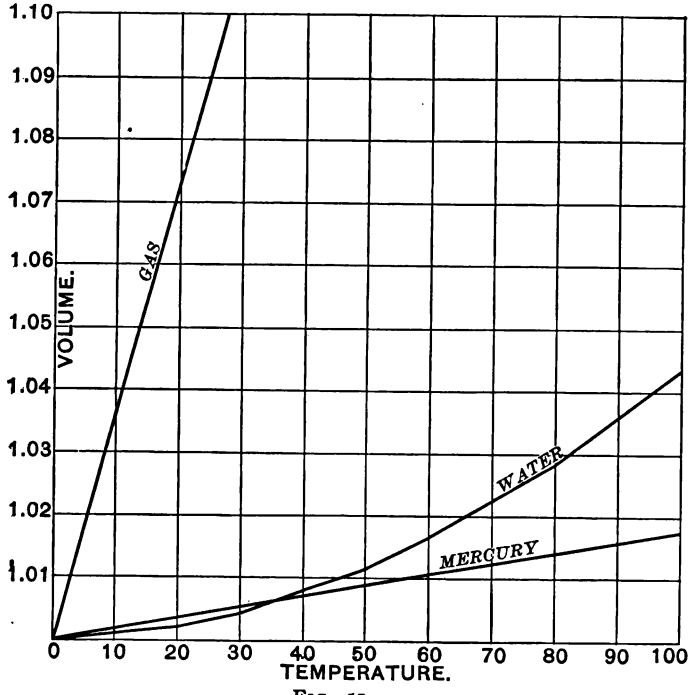


FIG. 51.

There are several requisites for a satisfactory fluid to be used in a thermometer. The substance should not change its properties on heating. It should have a large and uniform expansion coefficient and it should

be a good conductor of heat. The curves in Fig. 51 show the expansion of a gas, of mercury, and of water. From these it will be seen that a gas (and from what we know of gaseous conductivity, hydrogen gas) most nearly meets the requirements for a perfect thermometer fluid. Hydrogen thermometers are accordingly used as standards, but on account of the inconvenience of making temperature measurements with them they are replaced in practice by mercury thermometers.

Graduation of Thermometers.—Thermometers are regularly graduated by determining the height of the mercury column at two fixed temperatures, and by dividing the difference in these heights into some number of equal parts. In practice the fixed temperatures chosen are usually those of melting ice and of boiling water at a pressure of 760 millimeters of mercury.

On the Centigrade scale the temperature of melting ice is marked 0° and the temperature of boiling water 100°, the length of tube between these marks being divided into one hundred equal parts. On the absolute scale the melting point of ice is marked 273°, the boiling point of water 373°, and the space between graduated into one hundred equal parts. On the Fahrenheit scale, which is unfortunately in general use in our country, the melting point of ice is 32°, the boiling point of water 212°, and the space between divided into 180 equal parts. Nine degrees of the Fahrenheit scale are accordingly equivalent to five degrees of the Centigrade scale. Starting at the Centigrade zero, the Fahrenheit reading is 32°, then at 5° C. the reading will be 41° F., at 10° C. 50° F., and so following.

Comparison of Fahrenheit and Centigrade Scales. —To plot a curve showing the comparative readings of the Fahrenheit and Centigrade thermometers, proceed as follows:

Take a piece of cross-section paper, and beginning at the lower left-hand corner number the lines along the vertical side of the paper from 0 to 100, and along the bottom edge from 0 to 212, or as far as your paper will permit.

Begin at 32 on the bottom line (which is zero on the vertical scale) and indicate by crosses on the paper several corresponding points on the two temperature scales. Thus 15° on the Centigrade scale corresponds to 59° on the Fahrenheit scale, 35° on the Centigrade to 95° on the Fahrenheit, and 60° on the Centigrade to 140° on the Fahrenheit scale.

Draw a line through these corresponding points, and it will enable you to transform a reading from one thermometer scale to the other at a glance.

Referring to your curve, what Fahrenheit temperature corresponds to 20° C.?

At what temperature below zero are the readings of the two thermometer scales the same?

To Test the Fixed Points of a Thermometer.

LABORATORY EXERCISE 57.—Support the thermometer in a clamp with its bulb in a large funnel or other vessel from which water will drain off. Pack the vessel around the thermometer bulb and nearly to the zero point with shaved or finely broken ice. Read the thermometer, estimating tenths of a degree, at intervals of about a minute. When three successive readings are the same, record the temperature indicated, and the error in the location of the zero point.

Pour clean water into the small kerosene can used as a boiler in Laboratory Exercise 49. Pass the thermometer whose zero point you have just determined through a cork

which should be fitted into the neck of the can. Push the thermometer down into the can until its bulb is only one or two centimeters above the water, or until the 100 mark is just above the cork. Do not let the bulb dip into the water. Leave the spout of the can open for the escape of the steam, and boil the water vigorously over a flame. When the thermometer reading has become stationary for two minutes, read the boiling point of the water to one tenth of a degree.

Take the barometer reading. Allowing a change of temperature in the boiling point of 0°.37 C. for a change of one centimeter in the barometric height, calculate the boiling point of water at standard pressure as indicated by your thermometer. Calculate the error in your thermometer at 100°.

Remove the thermometer from the steam, repack it in ice, and determine its zero point again.

Glass after being expanded contracts very slowly, and the zero point of a thermometer is usually changed for some time after it has been heated to the boiling point.

Calibration of Thermometer Tube.—The graduation of a thermometer tube is based upon the assumption that the tube is of uniform bore. In the manufacture of thermometers the tube is calibrated by moving a short mercury column along the tube and measuring its length in different parts of the tube. This same determination can be made with a finished thermometer, but it is attended with difficulty and is not so satisfactory as the comparison of the thermometer with a standard thermometer whose corrections are known. This comparison is made by placing the two thermometer bulbs side by side immersed in water which is very slowly warmed and constantly stirred and reading simultaneously the temperature from the two thermometers. If a very accurate comparison is required, the readings must be made while the water is falling in temperature as well as rising.

CALORIMETRY

Definition.—The measurement of heat quantities is known as Calorimetry.

The Heat Unit.—For the measurement of heat quantities a thermal unit is necessary, just as a unit of length is necessary for measuring distances. In laboratory practice the thermal unit generally used is called the Gram-calorie. It is the quantity of heat necessary to raise the temperature of one gram of water one degree Centigrade. Within the limits of accuracy of our experiments this quantity is the same whether we raise the temperature of the water from 0° to 1°, or from 90° to 91°, though by careful measurements a difference may be shown.

Heat Capacity.—By the heat capacity of a body we mean the number of heat calories required to change its temperature one degree Centigrade.

Heat Capacity of a Calorimeter.

Laboratory Exercise 58.—A tin can holding about a pint and set in a wooden or pasteboard box and loosely packed round with wool or hair may be used as a Calorimeter, or a glass beaker holding about 400 cubic centimeters may be set inside a beaker of the next larger size and a little wool or cotton distributed in the space between to prevent convection currents in the air and be used for the same purpose. If very hot water is never used in the calorimeter, a cover is unnecessary.

Pour about 200 cubic centimeters of weighed or measured water in the beaker at a temperature about ten degrees below the room temperature. Stir the water with a thermometer, and take its temperature when the mercury column has become stationary, estimating tenths of a degree. From another vessel containing water about ten degrees warmer than the air, and whose temperature is known to a

tenth of a degree, pour in about 200 cubic centimeters of water. Stir rapidly and take the temperature to tenths of a degree as soon as the thermometer comes to rest.

Weigh or measure the water again to find how much you have poured in.

Assuming that water gains or loses one gram-calorie of heat per gram for each degree of temperature change, what should have been the temperature of the resulting water?

How much heat was lost to the air and the calorimeter? How much heat was required to change the temperature of the calorimeter one degree? Call this the heat capacity of the calorimeter.

(Thus 195 grams of water are warmed 10°, requiring 1950 calories; 200 grams of water are cooled 10°, losing 2000 calories. Heat lost to calorimeter and to air 50 calories. Calorimeter warmed 10°, capacity of calorimeter 5 calories.)

Make three determinations, and compare results. What is the mean of the three? What the greatest variation from this mean? What the extreme variation between any two determinations? How great an error in the final temperature reading of your thermometer would account for this error? If you make a mistake of one tenth of a degree in the final reading of your thermometer, how great an error in calories will it produce?

Determination of Latent Heat of Fusion of Ice.

Laboratory Exercise 59.—We have seen that a considerable quantity of heat is required to change ice into water without raising its temperature. This heat is required to give to the molecules the additional potential energy of the liquid state, and is called the Latent Heat of Fusion. We wish to find how many calories of heat become latent in melting one gram of ice.

Counterpoise your calorimeter on the platform balance, and pour in 300 or 400 grams of water warmed to about 60° C.

Have ready about 100 or 150 grams of finely broken ice drying on a cloth. Take the temperature of the water accurately, put in the dry ice and stir until it melts. Take the temperature again. Weigh to see how many grams of ice you have added.

Calculate:

(*a*) How many calories of heat were given up by the cooling water.

(*b*) How many calories were given up by cooling calorimeter.

(*c*) How many calories were used up in warming the melted ice from zero to the final temperature.

(*d*) How many calories were required to melt the ice.

(*e*) How many calories were required to melt one gram of the ice.

Make three determinations and take the mean. The latent heat of fusion of ice is taken as 80 calories. What is the error of your result? By what per cent of the true value is it wrong?

How many grams of ice could be melted by cooling 500 grams of water from 70° C. to 0° C.?

Determination of Latent Heat of Vaporization of Water.

LABORATORY EXERCISE 60.—The number of calories of heat required to change one gram of water into steam without increasing its temperature is called the Latent Heat of Vaporization of Water.

To provide steam free from water, pass the steam from the boiler through a trap made of a side-neck test tube or a piece of large glass tubing fitted with corks as shown in Fig. 52. If the latter device is used, the end of the delivery tube should be pushed past the end of the tube which brings the wet steam from the boiler, so that all the water may be left in the trap. The boiler may be the one used in Laboratory Exercises 49 and 57.

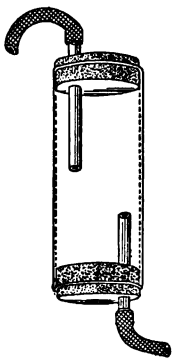


FIG. 52.

Counterpoise the calorimeter as before, pour in about 300 grams of water, if possible, cooled with ice to about 5° C. When dry steam is escaping rapidly from the delivery tube of your boiler, take the temperature of the cold water, and then suddenly insert the delivery tube into the cold water and allow the steam to condense until the water has been heated up to 50°

or 60°. Withdraw the delivery tube, weigh the water to find out how many grams of steam have been condensed, and calculate the latent heat of vaporization of water.

The latent heat of steam is given in the tables as 536 calories. What is the error of your determination?

How much ice could be melted by condensing 100 grams of steam and cooling it to 0° C.?

Fifty grams of wet snow was melted and warmed to 10° C. by 5 grams of steam. What part of the wet snow was ice and what part was water?

Specific Heat.—The number of calories required to change the temperature of one gram of a substance through one degree Centigrade is called Specific Heat of the Substance.

Determination of Specific Heat of Lead Shot.

LABORATORY EXERCISE 61.—Put 500 grams of fine shot in a small flask, and place the flask in boiling water. Insert a thermometer bulb in the interior of the mass of shot, and note its temperature when it becomes stationary. Put about 200 grams of weighed water in the calorimeter (preferably a few degrees below the room temperature), and take its temperature. Pour the shot quickly into the water, stir, and take the temperature as soon as it becomes constant.

Calculate the heat capacity of 500 grams of shot.

Calculate the specific heat of shot.

Determination of Specific Heat of a Liquid.

LABORATORY EXERCISE 62.—A "Calorifer" is prepared as follows: A glass bulb about one inch in diameter has attached a glass tube of about one millimeter bore. (Such bulbs and tubes are bought as air thermometers.) The bulb is carefully filled with clean mercury by successive heatings to drive out the air and allowing mercury to be drawn in as the contained air cools and contracts. The mercury column can always be let down into the bulb by using a fine wire. Make a mark on the stem at about the point to which the mercury column will rise at 30° C., and another mark just below the place to which the mercury column will rise at 100° C.

A calorifer in which the tube has been exhausted and sealed off is shown in Fig. 53.

Place the mercury bulb in boiling water and let the mercury expand and rise above the upper mark. Put 200 grams of cold water in the calorimeter, take its temperature, raise the mercury bulb by its stem out of the boiling water, dry it quickly, and at the instant when the mercury column has fallen to the upper mark immerse it in the cold water in the calorimeter. Hold it by the stem, and lift it out of the water at the instant when the top of the mercury column reaches the lower mark. Take the temperature of the water and determine how many heat calories the mercury has given off while its column was falling the distance between the two marks. This is the heat value of your calorifer.

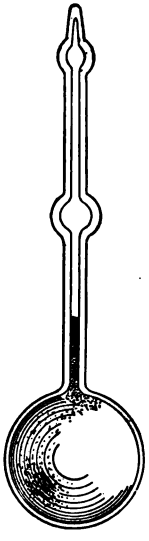


FIG. 53.

Put 100 grams of gasoline in your calorimeter and by means of your calorifer determine its specific heat. Do not allow the flame to come near your gasoline.

Specific Heats of Gases.—In our discussion of the kinetic gas theory (page 85) we saw that a gas heated under constant pressure will expand and do work, and that the work in ergs done by the expanding gas may be calculated by multiplying its increase of volume in cubic centimeters by the pressure in dynes under which it expands; that is, $W = (v_2 - v_1)p$.

It follows from what we have learned of the relation between heat and work that the work done by the expanding gas must require the expenditure of heat and that the gas will require more heat to raise its temperature by a given amount when it is allowed to expand under pressure than it will when it is confined to a constant volume. Gases accordingly have two specific heats, a specific heat at constant volume, and

a specific heat at constant pressure. The latter is greater than the former.

Relation between the Two Specific Heats of Air.

LABORATORY EXERCISE 63.—Fit a flask of about one-half liter capacity with an air-tight stopper through which a thermometer is passed. The flask should contain only thoroughly dry air, and the stopper should be air-tight.

Boil a sufficient quantity of water in a convenient vessel, and while the water is boiling rapidly read the thermometer and then lower the flask suddenly into the water to a mark made by fastening a wire or string around the neck of the flask. Note by the second-hand of a watch the instant when the flask is plunged into the water. Hold the flask in the water until the temperature of the enclosed air has risen forty or fifty degrees. It will probably be necessary to hold the cork tightly in place, as the increased pressure of the contained air may loosen it. Note the instant at which the flask is withdrawn from the water. Hold it until the mercury ceases to rise in the thermometer, which will be a few seconds after the flask is withdrawn from the water.

Record the time during which the flask was receiving heat from the water and the rise of the thermometer.

Loosen the stopper so that as the air in the flask expands it may escape into the outside air, and after its temperature has fallen to that of the first experiment repeat the experiment, holding the flask in the water for exactly the same length of time as before and noting the rise of temperature of the enclosed air.

In which case was the greater quantity of air heated in the flask? In which case was its temperature raised the more? Assuming that the flask received the same amount of heat from the water in both cases, in which experiment was the specific heat of air greater?

By how many cubic centimeters would a half liter of air under standard pressure expand in being heated from 20° C. to 60° C.? How many ergs of work would it do in expanding?

Energy Value of the Calorie.—In referring to Dr. Joule's experiments on the relation of heat to work (page 142), it was stated that he found that 773.64 foot-

pounds of work when changed into heat would raise the temperature of one pound of water by one degree Fahrenheit.

A Fahrenheit degree is five ninths of a Centigrade degree; how many foot-pounds of energy would be required to raise the temperature of a pound of water one degree Centigrade?

To what height can a mass of water be raised by the energy required to warm it one degree Centigrade?

The Yosemite Fall is 2548 feet high. How much warmer should the water be in the stream below the fall than in the stream above?

The mean value of the best determinations of Joule's equivalent shows that the energy required to warm a gram of water by one degree Centigrade is sufficient to raise a gram weight 427 meters in the mean latitude of the United States. Since the weight of a gram varies with variations in gravitation upon different parts of the earth, while the heat energy of a gram calorie is not variable, it is desirable to be able to state the energy equivalent of the gram calorie in invariable energy units. Expressed in the C.G.S. system, this value is taken as forty-two million ergs. This quantity is accordingly known as *the dynamical*, or *the mechanical, equivalent of the heat unit*, and is Joule's Equivalent expressed in ergs.

What part of a gram calorie is used to do the work of expansion of a liter of air under standard pressure when warmed from 20° C. to 70° C.?

Explain the apparent loss of kinetic energy of the two putty balls referred to on page 136.

HEAT ENGINES

Definition.—Machines in which heat is transformed into mechanical energy and applied to the performance of work are known as Heat Engines. The steam

engine is the best known and most important type of heat engines.

The Steam Engine.—The steam engine is a machine in which the expansive force of steam is used to drive a piston forward and back in a cylinder, while the motion of the piston is utilized to drive other machines or to propel the engine.

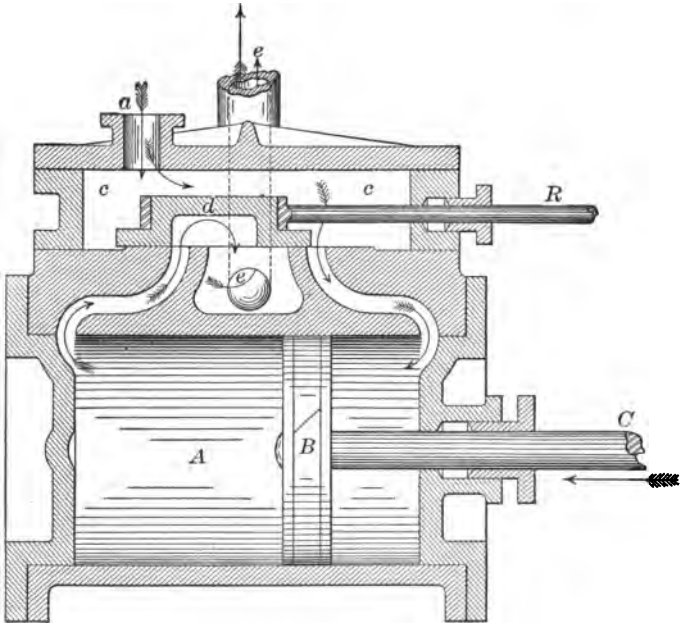


FIG. 54.

The principal working parts of the modern steam engine are shown in Figs. 54 and 55. In Fig. 54 the cylinder and connected parts are shown in plan (that is, you are supposed to be looking down upon them), and in Fig. 55 the engine is shown in elevation. The lettering of parts is the same in both figures.

Thus *A*, Fig. 54, represents the *cylinder* in which the tight-fitting *piston B* is driven back and forth as the steam enters the cylinder alternately on one side of it or on the other. Attached to one side of the cylinder is the *steam chest*, or *valve chest*, *c*, from which the steam is admitted to the cylinder through openings at its ends called *steam ports*. These ports are alternately connected with the steam chest and with the *exhaust pipe e* by means of the *slide valve d*.

In Fig. 54 the piston is represented as moving toward the left, as shown by the arrow near the *piston rod C*. The slide valve is also moving in the same direction, but is nearly at the end of its stroke. The steam port back of the piston is in communication with the steam chest, while the steam port in front of the piston is in communication with the outside air or the condensing chamber through the exhaust pipe. The piston is accordingly receiving the full pressure of the steam from the boiler on one side, and a pressure of an atmosphere or less on the other side.

Before the piston reaches the end of its stroke, the slide valve will be drawn back, closing the port through which the steam now enters, and an instant later the other port will be opened into the steam chest and the motion of the piston will be reversed.

In Fig. 55 a side view of the engine is shown. The valve chest with its slide valve, its *eccentric rod R*, and the *eccentric wheel E* as it is mounted on the *main shaft L* are shown below. Their position in the engine is on the side opposite the observer. The *steam pipe a* is represented as turned upward after leaving the valve chest, and at *b* is shown the position of the *throttle valve* by which the supply of steam from the

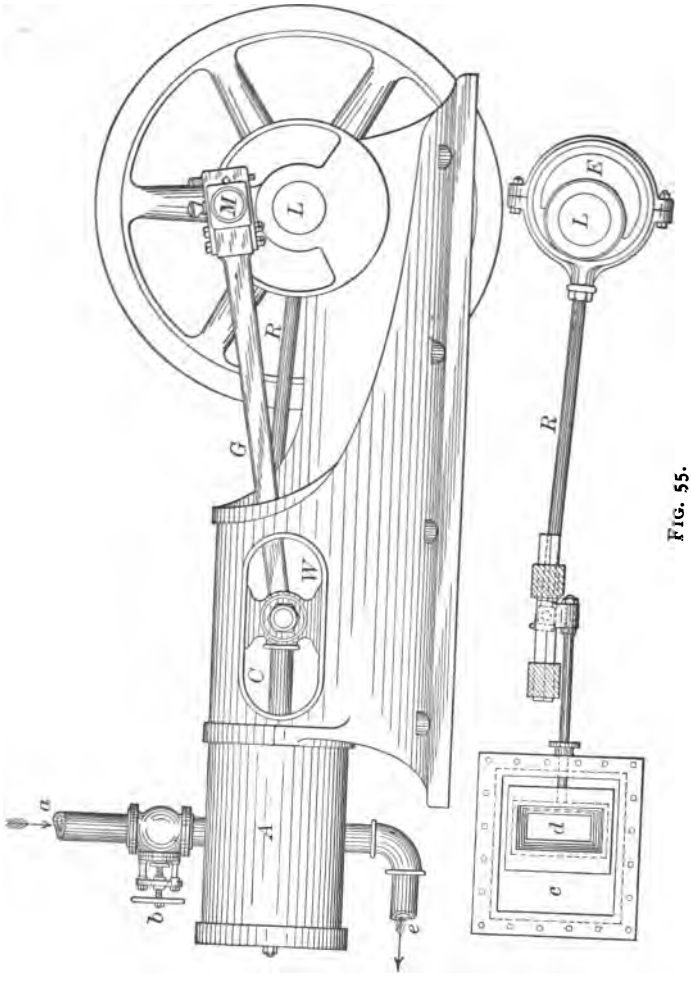


FIG. 55.

boiler may be regulated or cut off. The *exhaust pipe e* is represented as turned downward below the cylinder.

The *piston rod C* is shown with its *parallel-motion guides W* at its junction with the *connecting rod G*. The connecting rod is attached by means of a boxing to the *crank pin M*, thus enabling it to turn the crank, which is keyed to the *main shaft L*.

The heavy *fly-wheel* mounted on the main shaft is to steady the motion of the shaft. During a part of its revolution it is being accelerated by the energy derived from the piston, and during another part it is giving off its energy to accelerate the motion of the piston. In this way the jerky motion of the piston is transformed into the steady motion of the main shaft.

The fly-wheel may also be used as a *driving-wheel*, in which case it carries the belt by which the energy of the engine is transferred to another machine.

High-pressure and Low-pressure Engines. — Engines in which the exhaust pipe opens into the external air (or, as in the railroad locomotive, into the chimney of the furnace) are known as high-pressure engines. In such engines the piston must always be forced against the pressure of the atmosphere in addition to the other load it must move. In low-pressure, or condensing, engines the exhaust pipe opens into an exhausted air-tight vessel called the condenser, where the steam is condensed by a spray of cold water. The heated water from the condenser is then pumped into the boiler and used again in the production of steam.

The Gas Engine.—Another form of heat engine which is very extensively used is the gas engine. In this engine a mixture of air and coal gas or gasoline

vapor in proper proportions is introduced into the cylinder, the admission is cut off, and the mixture exploded by an electric spark. The explosion develops a sufficient quantity of heat to raise the enclosed gas to a high temperature, and the expansion of the heated gases drives the piston before them until the stroke is completed. The gaseous products of the combustion are then expelled by the return stroke of the piston. The second stroke of the piston allows a new charge of mixed gases to enter the cylinder, the return stroke compresses them and they are then exploded by another spark. Thus the piston makes two strokes and returns, giving two complete revolutions of the main shaft, for each explosion. The piston in the gas engine accordingly receives one impulse while that of the steam engine receives four.

Fig. 56 shows a plan of a gas engine in which the parts are lettered like the corresponding parts of the steam engine in Figs. 54 and 55. *A* represents the *cylinder* with only one cylinder head, instead of two as in the steam engine. *B* represents the bucket-shaped *piston*, which, on account of its long bearing on the cylinder wall, does not need a piston rod and parallel-motion guides. The *connecting rod G* is hinged to the piston by the steel bolt *D*, known as the *cross-head gudgeon*, which passes through the head of the connecting rod, and upon which the head of the connecting rod turns as the other end turns upon the crank pin.

The mixed gases enter the chamber *c*, from which, by the opening of the valve *d*, they enter the *explosion chamber E*, where they are ignited by the *sparking apparatus F*, which is joined to an induction coil and

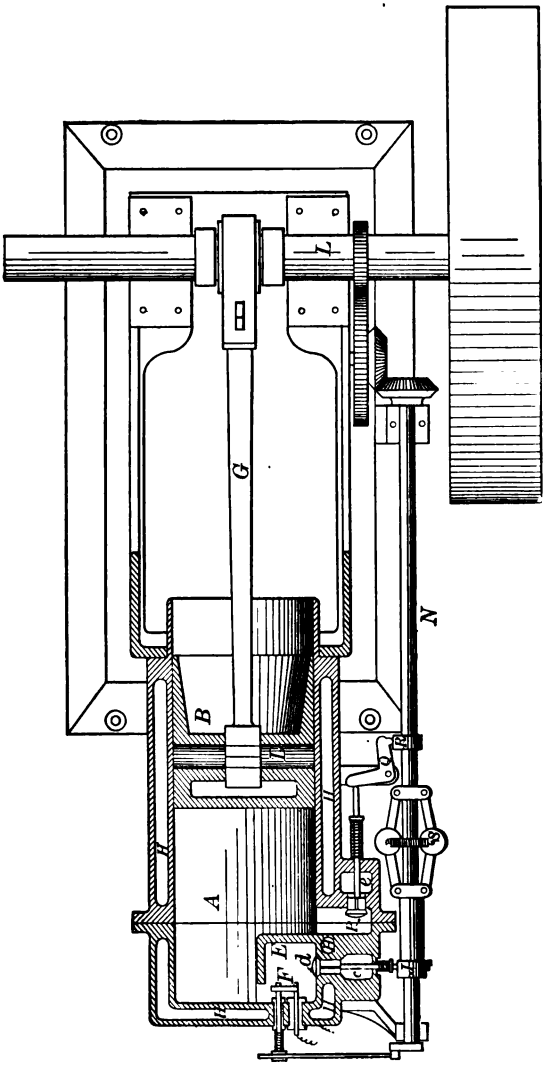


FIG. 56.

a voltaic battery. The *admission valve d* is opened by the cam *J* which is mounted on the *governor shaft N*, and which is controlled by the *governor S* so as to vary the amount of the entering gas. The products of combustion are removed through the valve *P* which is opened at each revolution of the governor shaft by means of the crank *Q* and the cam *R*.

On account of the great amount of heat generated by the explosion of the gases, it is necessary to provide the cylinder with a cooling apparatus. In the figure the spaces marked *H* are cavities for the circulation of cold water about the cylinder.

In Fig. 57 the parts are lettered as in Fig. 56. The pipe *a* is for the entering gas. At *b* is shown the position of the *throttle valve*, and the *exhaust pipe* is shown at *e*. The pipes *H* and *H'* are for the water circulation which cools the cylinder.

Efficiencies of Engines.—The efficiency of the best gas engines is nearly twice as great as that of the best steam engines; that is, nearly twice as large a percentage of the total energy of combustion of the fuel used is utilized in the gas engine as in the steam engine. In the latter a large part of the heat is necessarily lost in the furnace and boiler before it reaches the cylinder, while in the former the combustion takes place and the heat is generated in the cylinder itself. Still the loss of energy is very great in the gas engine. A very high temperature is developed by the explosion, the cylinder walls are heated, and the water which circulates through the cylinder jackets carries away a great deal of heat. The gases which escape through the exhaust pipe have not transformed all their molecular energy into mechanical energy, and they are

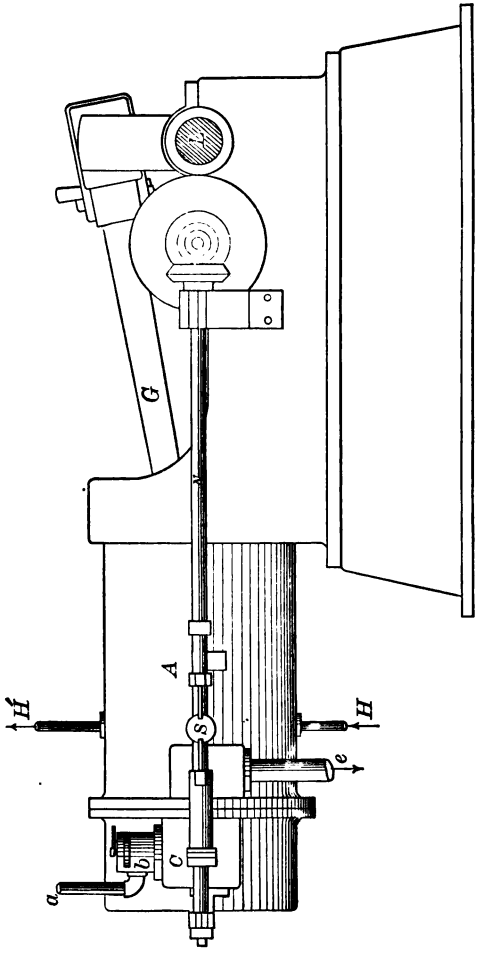


FIG. 57.

accordingly still hot. Fully three fourths of the energy liberated by the explosion is used up in these different ways, so that a very good gas engine does not transform more than 25 per cent of the total energy of the combustion into mechanical work.

The efficiency of a steam engine rarely reaches 15 per cent.

PROBLEMS.—A steam engine of 10 horse-power is used to raise water from a well 50 feet deep. If a gallon of water weighs 8.3 pounds, how many gallons per minute can be raised by the engine?

A 5-horse-power engine works a paddle wheel in a vessel of water containing 10 kilograms. Neglecting the heat given off to the containing vessel, how long will it take to raise the temperature of the water 50° Centigrade?

If the efficiency of the above engine is 10 per cent, how many calories of heat are given off by the coal during the experiment?

PART IV

WAVE-MOTION AND SOUND

SOUND

Scope of the Subject.—The form of energy transference known as Wave-motion is best studied in its relation to the phenomena of Sound and Light. Sound and Light differ from other branches of Physics in that they involve both a physical and a physiological side. The physical side of the subject of Sound is principally concerned with wave-motions in elastic bodies. The physiological side is concerned with the sensations produced in the hearing organ by means of these wave-motions.

VIBRATION OF SOUNDING BODIES

First Law of Sound.—The fundamental proposition in the study of Sound is that *All sounding bodies are in a state of vibration.* These vibrations may be observed in a number of characteristic sounding bodies by means of the following experiments.

Experiments on Sound Vibration.

LABORATORY EXERCISE 64.—*a.* Sound a tuning fork by striking it against a cork or against the knee, and feel the vibrations of the prongs. Of the stem. Touch the prongs

and the stem to water. What proofs of vibration do you observe? Stop the vibrations with the fingers. Can you make the fork sound when it is not in vibration?

b. Stretch a fine wire by means of piano pegs on a board or a sounding box, and cause the wire to sound by bowing it with a violin bow. Prove that the wire is in vibration while it is sounding. Explain your method of proof.

c. Fill a round glass vessel, as a finger bowl, or a wide sugar bowl with a smooth rim, half full of water and make it sound by bowing across its rim. Use plenty of rosin on the bow. Does the glass vibrate? How do you know?

d. A round or square brass plate with smooth edges fastened rigidly in a horizontal position by a screw or a clamp at its center is called a Chladni's Plate. Sound the plate by bowing across its edge with a well-rosined bow. While it is sounding, sprinkle sand upon the plate. Is it in vibration? Does it vibrate as a whole, or are there places of rest? Must the vibrations on opposite sides of the places of rest be in the same, or in opposite directions?

e. A wooden organ pipe with one thin side may be laid upon the table with the thin side uppermost. Sound the pipe by blowing, and sprinkle sand upon the thin side. What evidences of vibration in the pipe do you detect?

f. A glass tube three or four feet long and from a half inch to an inch in internal diameter is held in a horizontal position by a clamp * at the middle of the tube. Cork one end of the tube and scatter along the inside of the tube dry cork dust, made by filing a cork which has been thoroughly baked in an oven. Dampen a piece of flannel with water, and holding it in the hand grasp the tube with it and stroke it lengthwise until it gives off a clear sound. What evidences of vibration do you see in the cork dust?

Remove the cork from the end of the tube and cause it to sound as before. Does the cork have anything to do with the vibrations of the cork dust in the tube? If the tube vibrates lengthwise, what effect will the cork in its end have upon the air inside? If the ends of the tube vibrate sidewise, will the cork set the inside air in vibration? What do you conclude about the nature of the vibrations of the tube?

* For clamping the tube, bore a hole slightly smaller than the tube in a piece of board about an inch thick and two or three inches wide, and

Observe carefully the peculiar figures formed by the dust particles in the tube. These will be considered later.

g. A metal or cardboard disc with a row of round holes spaced at equal distances near its edge and mounted so that it can be set in rapid rotation is called a Disc Siren. Set the disc in rapid rotation and blow through the holes by means of a piece of rubber tubing. Can you produce a continuous sound in this way? What vibrations may be regarded as the cause of the sound? Can sound be caused by the vibrations of a gaseous body?

All of the above experiments show that sound is associated with the vibrations of material bodies. In the following experiments we wish to find what kinds of bodies may transmit these vibrations.

Transmission of Vibrations by Solids, Liquids, and Gases.

LABORATORY EXERCISE 65.—Sound a tuning fork and hold

with a saw cut a slit from the end of the board into the hole. This will allow the hole to spread so that the tube can be pushed through it. Push

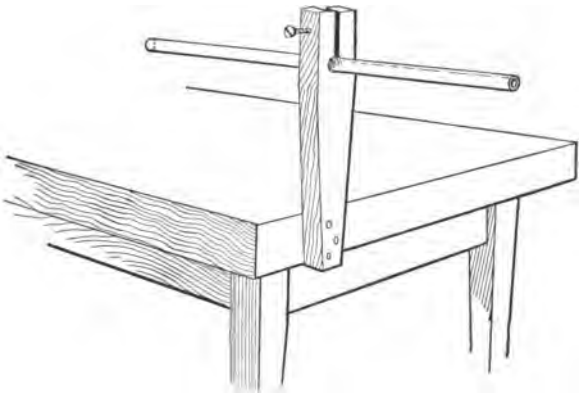


FIG. 58.

the tube through to its middle, and fasten it in position by drawing the two sides of the slit together by means of a screw, as shown in Fig. 58. Then screw or clamp the board to the table so that the tube is horizontal.

the end of its stem tightly against the table. Does the fork continue to vibrate as long as when held loosely in the fingers? Why? Note the increase in the loudness of the sound.

Since the vibrating prongs set but little air in motion, they give off their energy very slowly. When the end of the stem is held against the table the energy is given off rapidly to the table and by it to the air, and consequently more of it enters our ears in a given time. We accordingly recognize the sound as louder.

Find a box, as a cigar box, which sounds loudly when touched by the stem of the fork. Hold the stem of the sounding fork against the end of a short rod of wood, and press the other end of the rod upon the box. Does the rod transmit the vibrations of the fork to the box?

Try in the same way to pass the vibrations of the fork through iron, glass, India rubber, and other substances, and note which ones are good transmitters of vibrations.

Place a glass of water upon the box, and holding the stem of the sounding fork against a small block of wood, place the block in the water, taking care that it does not touch the glass. Are the vibrations of the fork transmitted by the water?

Two large tuning forks are mounted upon sounding boxes and so adjusted that when one is sounded near the other, the other takes up the sound. Since the second fork is set in vibration when it sounds, the vibrations of the first fork must have been transmitted to it by some medium.

Let another person hold one of the forks by its box while you stand near and cause the other one to sound loudly by bowing it across one of the prongs. Are the vibrations of the sounding fork transmitted to the other by the intervening air? Take as many precautions as you can to prevent the transmission of the vibrations by solids or liquids and satisfy yourself whether sound vibrations may be transmitted by air.

A string telephone is constructed by stretching a piece of animal membrane, thin rubber, or parchment paper over the end of a small box from which the bottom has been removed and connecting the center of this membrane to a string or thread. When the string is tightly stretched between two such telephones, a conversation can be carried on over the

line. Explain the sound vibrations in the box which is held to the ear.

Vibrations not Transmitted by a Vacuum.—The above experiments show that sound vibrations may be transmitted by solids, liquids, or gases. That they may not be transmitted by a vacuum is shown as follows:

A loud-ticking watch or other sounding body may be placed upon a loose pad of cotton or wool under the receiver of an air-pump and the air may be exhausted by means of the air-pump. A noticeable decrease of the sound will be observed as the air in the receiver becomes rarefied. It is impossible with an ordinary air-pump to exhaust all the air from the receiver, and the sounding body cannot be supported so that it will not be in contact with other bodies which may carry the vibrations to the outer air. Experiments have been made in this way, however, which show conclusively that sound vibrations are not transmitted by a vacuum. It follows that sound vibrations are not transmitted by the Luminiferous Ether.

WAVE-MOTION

How Vibrations are Transmitted.—We have seen that the energy of sound vibrations may be transmitted by solids, liquids, and gases. We now wish to study the manner in which this energy is transmitted by the bodies which serve as its carriers.

Wave-motion in Spring Cord.

LABORATORY EXERCISE 66.—A long cord of wire wound in the form of a spiral spring should have one end attached to a rigid support, preferably to a high ceiling. Taking the free end of the cord in the hand and giving a quick jerk to one side and back, throw a short portion of the cord into a

loop or kink, and notice that this loop travels along the cord from your hand to the fixed end of the cord. If both ends of the cord be held rigidly fixed after the loop is formed, it may travel forward and back several times the length of the cord before its energy is all used up in the work done in bending the cord. Such a traveling loop is called a Wave. Notice that the wave travels in one direction along one side of the cord, and that when it is reflected at the end of the cord it travels back along the opposite side.

Since the particles of the cord vibrate at right angles to the length of the cord and hence to the direction of motion of the wave, such a wave is called a wave of transverse vibration.

Stretch the cord and hold it tightly with one hand about six inches from the free end. With the other hand pull the free end of the cord, stretching the part between the hands, and let it fly back with a snap. Observe the pulse that is set up in the cord. Make one that will travel several times the length of the cord before it comes to rest.

If the cord was properly held in the last experiment, no sidewise vibration was observed. The stretched end of the cord when it shortened after being released compressed the coils of the wire immediately in front of it, these (in separating) compressed other coils in front of them, and thus a pulse or wave of compression was sent along the wire. Since the vibrations of the wire were forward and back in the direction of propagation of the wave, this wave is called a wave of longitudinal vibration, or a compressional wave. It will be seen at once that a wave of longitudinal vibration must cause a compression or expansion of the body by which it is transmitted.

Two Forms of Wave-motion.—These are the two forms of wave-motion usually distinguished. In one form the particles of the vibrating body are displaced sidewise and back across the path of the wave, in the other they are pressed together and then expand in the direction of motion of the wave. Since in expanding they do not stop when the position of normal equi-

librium has been reached, the compressed part of the wave is regularly followed by an expanded part.

What name do we give to the force which causes the coils of wire to return to their original position after they are stretched or bent?

By means of what force may the wave be said to be propagated along the wire?

Why are wood and glass better conductors of vibrations than soft rubber?

What kind of elasticity is found in fluid bodies? What kind of waves would you expect such bodies to transmit?*

The Wave Machine.

LABORATORY EXERCISE 67.—An efficient wave machine may be constructed as follows: Into a bar of wood about ten feet long drive double-pointed carpet tacks along one side at regular intervals of about four inches. Procure a long, fine copper wire (a waxed thread may be used, but becomes more easily tangled than the wire) and pass it through between the tacks and the bar, stringing a large brass button or a small lead weight † upon it between each pair of tacks and using a heavy iron or lead ball in place of the button at one end of the series. Allow the wires with the suspended buttons to hang down about two feet below the bar, as shown at *a* in Fig. 59. After the buttons have all been adjusted to the same height, tie pieces of thread around each pair of wires between adjacent buttons, and

* An exception to this law is apparently seen in the most familiar form of waves, viz., the waves on the surface of water. This apparent exception disappears when it is remembered that these water waves are not transmitted by the elasticity of the water, but by gravitation. The top of the wave is not pulled down by elasticity, but by gravitation, and the energy of the wave is like the energy of the gravitation pendulum.

† Weights suitable for the wave machine may be cut from a piece of small lead pipe and strung upon the wire. If very fine wire is used, they should not weigh more than about 5 grams, and should all be of the same weight.

draw the wires together as shown in *b* in the figure. Slip the thread loops down to the same height on all the wires.

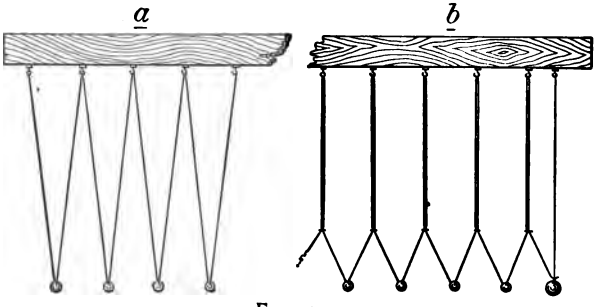


FIG. 59.

Set the heavy ball in motion, and observe the passage of the wave along the line of buttons.*

Set up a wave of transverse vibration in the wave machine. A wave of longitudinal vibration.

By what means is the vibration transmitted from one button to the next one?

Could you set up a wave of transverse vibration in a row of disconnected pendulums?

Could you set up a longitudinal wave in such a row of pendulums if they were not allowed to strike each other in their swings?

When a row of "collision balls" such as were used in Exercise 18 are all of the same mass and are hung in a line touching each other, if a ball at one end be pulled away from the others and allowed to swing against the one next to it, the ball at the farther end of the line may be set in motion while the intervening balls apparently remain at rest. Does a compressional wave pass through the line of balls? If so, explain how.

Wave-front.—When a wave-motion passes along a line, the wave-front is a point in the line. If a wave-motion passes through a plane, the wave-front is a line

* The vibration period of these waves may be varied by any desired amount by clamping the wire of the heavy pendulum so as to change its vibrating length, or by giving it forced vibrations with the hand.

of the plane. When a wave-motion passes through a medium having three dimensions, the wave-front is always a surface. When a wave passes along the spring cord, for example, the wave-front is a cross-section of the cord.

When a wave is set up within an isotropic substance, since the properties of the substance are the same in all directions the wave will spread out in all directions with equal velocities, hence the wave-front will be the surface of a constantly enlarging sphere.

Wave-train.—We have thus far considered but one wave at a time. If the wave under consideration be produced by a periodically vibrating body, as a tuning fork, it will be followed at equal distances by other waves of the same kind which will all travel at the same rate. Such a series of successive waves is called a Wave-train.

If the vibrations of the body producing the waves do not occur at regular intervals, its vibration is said to be aperiodic, and its waves do not follow each other at regular distances and hence do not constitute a wave-train.

In sound waves we generally have to deal with wave-trains.

Wave-length.—In wave-trains, the wave-length is the distance between two successive wave-fronts, or, what is the same thing, the distance between the corresponding parts of two successive waves. In water waves, the elevated part of the wave is called the crest, and the sunken part is called the trough. A wave-front is a continuous crest or a continuous trough, and a wave-length is the distance from one crest or trough to the next one.

Relation of Wave-length to Velocity of Propagation.—If a wave-train be produced by a body having a constant period of vibration, the wave-length will vary as the velocity with which the waves travel through the conducting medium. It will be the distance which one wave travels before the next wave is produced. If the wave velocity should be doubled, the wave-length would also be doubled.

Relation of Wave-length to Period of Vibration.—The wave-length of a train of waves in a given substance will vary directly as the period of vibration of the body by which they are caused. Thus if the velocity of a wave-train be one thousand feet a second, a tuning fork vibrating one hundred times a second will produce waves ten feet long, and one vibrating two hundred times a second will produce waves five feet long. The longer the vibration period of the fork, and accordingly the fewer its number of vibrations a second, the longer the waves in its wave-train.

Let v = the velocity of wave propagation, n = the number of vibrations a second of the inducing body, and λ* = the wave-length, and give an expression for v in terms of n and λ.

Wave Amplitude.—The greatest displacement of a vibrating particle in a wave from its normal position of rest is called the Amplitude of the wave. The amplitude of a water wave is the vertical distance from the water level to the crest or trough of the wave.

Wave Induction.—We have seen that the energy of a vibrating body may be transmitted in the form of waves by any elastic medium with which it comes in contact. When this occurs, the waves in the trans-

* The Greek letter lambda.

mitting medium are said to be induced by the vibrating body. These waves may in turn induce vibrations in some other elastic body at a distance from their original source.

Induced vibrations are of two classes, Sympathetic or Resonant Vibrations and Forced Vibrations. In the one case the body is set vibrating in its natural period by a series of properly timed impulses, and in the other case it is forced into vibrations of an unnatural period.

Resonance.

LABORATORY EXERCISE 68.—(*a*) Suspend a heavy weight, as a pail of sand, by a strong cord so that it may swing as a pendulum. Then by means of a series of slight impulses applied just as you would apply them to a person in a swing, set the heavy pendulum in vibration. In this case, the total energy of the vibrating pendulum is nearly the sum of all the quantities of energy given to it by the original impulses.

Can you produce the same effect by impulses applied slower or faster than the ones previously used? Why?

(*b*) Explain how the waves sent off by one tuning fork can set another tuning fork in vibration.

What is necessarily true of the vibration periods of the two forks?

(*c*) Take a glass tube about 30 centimeters long and about 2 or 3 centimeters in internal diameter and stand it upright in a tall cylinder or other deep vessel of water as in Fig. 60. Hold a sounding tuning fork with the side of one prong directly above the open end of the tube, and raise or lower the tube in the water until the column of air in the tube sounds loudly in unison with the fork. Such a tube is called a Resonance Tube.

What reason have you for thinking that the air column is in vibration?

Why will not a longer or a shorter column of air vibrate as well?

Repeat the experiment with another fork having a different vibration period. Are the vibrating air columns of the same length for the two forks?

(*d*) Hold a vibrating tuning fork to the mouth of an organ pipe which gives the same note as the fork. Is the organ pipe also a resonance tube?

(*e*) Take a wide-mouthed glass vessel, as a fruit jar or a

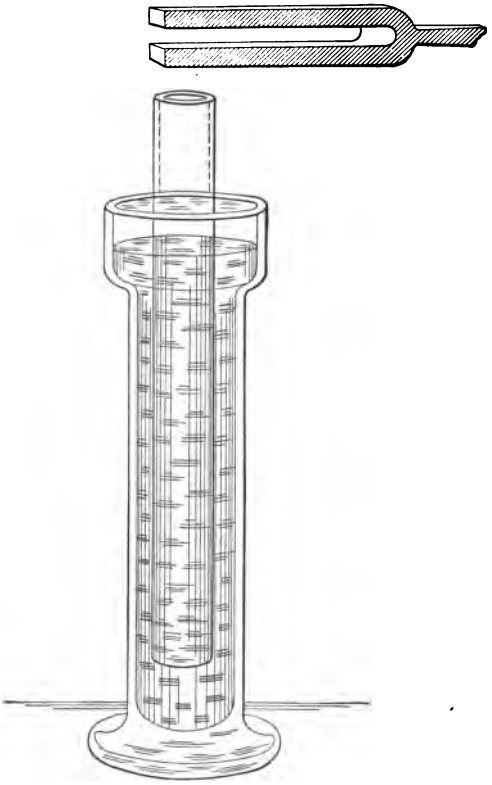


FIG. 60.

tumbler, and cover its mouth with a piece of glass or heavy cardboard, leaving only a narrow opening at one side of the vessel. Hold a vibrating tuning fork above this opening and adjust the width of the opening by sliding the cover of the vessel until you find a position where the enclosed air will

vibrate in unison with the fork. Such a vessel is called a Resonator.

Does the same resonator resound equally well to forks of different vibration period?

Does the enclosed air in the resonator have a natural period of vibration, as a pendulum does?

To show the vibrations of the air, stick the cover in place with wax, and then stretch a soap film over the opening by inverting the resonator in a soap solution, or by spreading the film over the opening by means of a soft brush. Then hold the vibrating tuning fork so that the resonator will resound to it and observe the soap film over the opening.

A permanent resonator may be made by pasting a piece of wet linen paper over the mouth of a jar or tumbler and allowing it to dry, then cutting an opening in the paper at one side of the jar and enlarging it until the resonator is properly tuned. The size of the opening should be determined beforehand by use of a glass or cardboard cover.

When such a resonator resounds to a fork, the vibrations may be shown by scattering sand on the paper and inclining the resonator so that the sand will nearly slide off when the paper is at rest. Then when the paper vibrates the sand will slide down the incline.

(*f*) Hold a vibrating tuning fork in front of your mouth and try to adjust the mouth cavity so that it will serve as a resonator for the fork.

The cavity of the external ear serves as a resonator for certain very shrill sounds, and for this reason these sounds seem very loud and sometimes become painful. It is for this reason that the sounds of some insects, as the chirping of a cricket, are heard so plainly.

Forced Vibrations.—If a string be tied to the heavy pendulum used in the preceding exercise, the pendulum may be made to swing faster or slower than its normal rate by pulling on the string. The pendulum is then said to make forced vibrations.

When the stem of a vibrating tuning fork is held against a board, the surface of the board is forced into

vibrations of the same period as the vibrations of the fork. Thus the same board can be made to vibrate to any fork. When tuning forks are mounted on boxes to reinforce their sound, a box is usually chosen which is a resonator for the particular fork which is to be mounted upon it. The sound of the fork is then reinforced by the forced vibrations of the sides of the box and the sympathetic vibrations of the enclosed air.

The vibrations of the sounding boards of musical instruments, as the piano, the violin, and the guitar, are forced vibrations. The vibrations of the air columns in wind instruments are sympathetic vibrations. The sounds of the voice in speaking or singing are caused by sympathetic vibrations, and their vibration period is changed by changing the shape of the resonating cavities of the mouth and pharynx or by varying the size of their openings into the external air.

Reflection of Waves.—In the experiments with the brass spring-cord, you saw that a wave traveling along the cord is reflected at the fixed end and travels back along the opposite side of the cord. Since only a part of the energy of the wave could be given off to the support at the fixed end of the cord, the rest traveled back in the form of a new wave.

The same phenomenon may be observed in the wave machine by sending a single wave along the row of buttons. The end button cannot give off its energy to any other body, so it swings back to the other side of its arc and thus starts a wave in the opposite direction along the connected row of buttons.

The reflection of sound waves is also a well-known phenomenon, and gives rise to echoes. When a sound wave traveling through the air meets an obstruction,

part of its energy is given to the obstruction and the rest is turned back as a reflected wave.

Interference of Waves by Reflection.—When advancing and reflected wave-trains are traveling through the same medium they often interfere with each other's vibrations and produce new phenomena. One of the commonest effects of interference by reflection is the production of standing waves.

Standing Waves.

LABORATORY EXERCISE 69.—Set the heavy pendulum of the wave machine swinging and observe the wave-train produced as it passes along the row of buttons and returns after reflection. You will see that at certain points along the line the advancing and reflected waves meet, and that the successive waves of the two trains meet at the same points. At these points the pendulums tend to swing under the influence of two equal and opposite impulses, and the result is that they do not swing in either direction. You will probably be able to observe several of the pendulums which are practically at rest while those on either side of them are in full vibration. The waves produced by the inducing pendulum accordingly appear to stand still and cause the same pendulums to vibrate all the time, hence they are called standing waves.

Take the free end of the spring-cord in the hand and start a transverse wave along it. Just at the instant when this wave is being reflected, start another to meet it. If properly timed, they will meet and pass each other at the middle of the cord, and this part of the cord will remain at rest while they are passing.

Swing the end of the cord back and forth so that it will vibrate in two parts with a place of no vibration between them. Cause it to vibrate in three parts. In four parts.

When the vibrations are properly timed, the advancing and reflected wave-trains always meet at the same places and the cord vibrates in standing waves.

Standing waves as distinguished from moving waves have certain fixed parts. In a moving wave, every particle which takes part in the wave-motion goes through the same series of vibrations as the other particles of the wave and there are

no places of rest and no parts of greatest vibration. In standing waves, some parts of the cord do not move at all.

The places of rest in a standing wave are called Nodes. The places of greatest vibration are midway between the nodes, and are called Loops.

The wave-length of a standing wave is taken as the distance between the parts of two adjacent waves which are in the same phase of vibration. Since successive loops are always in opposite phases of vibration, a complete wave-length always takes in two loops and two nodes.

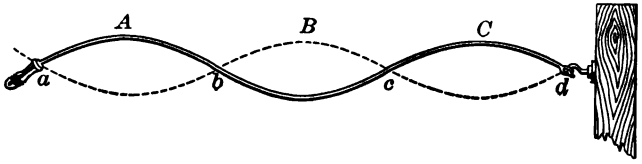


FIG. 61.

Fig. 61 shows the form taken at a particular instant by the vibrating cord when it is thrown into standing waves. The nodes are lettered *a*, *b*, *c*, and *d*, and the loops *A*, *B*, and *C*. A wave-length is the distance from *A* to *C* or from *a* to *c*, or from *b* to *d*.

We are now ready to explain the peculiar forms taken by the cork dust in the vibrating tube used in Exercise 64. The longitudinal vibrations of the tube caused the cork in one end to set up waves in the enclosed air. These waves were reflected at the open end of the tube, just as the waves are reflected from the free end of the wave machine, and in returning along the tube set up a row of standing waves in the air in the tube. The cork dust is set in motion by the vibrations of these air waves. The places where the cork dust remains at rest are the nodes, and the places where it is most violently agitated are the loops of these waves. Thus *a*, *b*, and *c* in Fig. 62 are nodes.

The wave-length of these particular sound waves in

air is the length of two of the cork-dust segments, best measured from one node to the second one on either side of it, as from *a* to *c*.

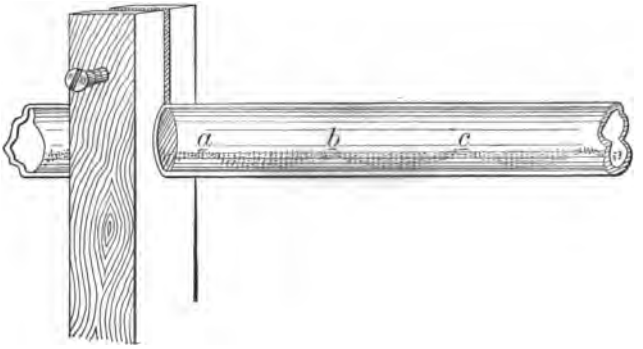


FIG. 62.

Measure a number of the segments and see if they are of uniform length.

If the velocity of these sound waves is 338 meters a second, what is the vibration period of the cork in the end of the tube?

Interference of Sound Waves.

LABORATORY EXERCISE 70.—We have seen that standing waves may be produced in elastic bodies by the meeting of similar wave-trains going in opposite directions. In the case of the glass tube, we saw these standing waves produced by the meeting of trains of sound waves in air. We now wish to study some of the other phenomena of the interference of sound waves.

(*a*) Sound a tuning fork, and holding the side of the prongs near the ear rotate the stem of the fork in the fingers. As the fork turns around, you will notice that when the corner of its nearest prong is turned toward the ear the sound of the fork cannot be heard, but that when the sides or the edges of the prongs are turned toward the ear the sound becomes very plain.

The explanation of this phenomenon is as follows: When the fork sounds, its prongs vibrate always in opposite direc-

tions. This may be readily shown by making a tracing on smoked glass by means of little points attached to the ends of the prongs of a vibrating fork. Fig. 63 is photographed

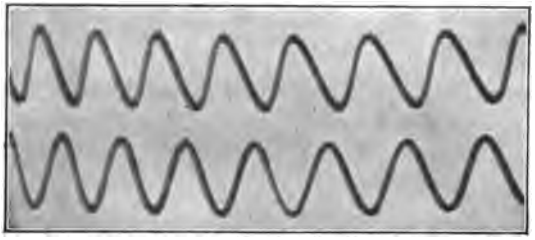


FIG. 63.

from such a tracing. As the prongs separate they drive away the air on the outer side of both, while the air near their edges rushes into the enlarged space between them. When the prongs approach each other, the air between them is compressed and forced outwards, while the air on the outer sides of the prongs follows them inward toward the center.

This condition is represented in Fig. 64, where you are supposed to be looking directly toward the ends of the prongs. The arcs of the circles shown in dotted lines are to represent the region in which the air is vibrating toward the fork, and the arcs shown in entire lines represent the regions where the air is vibrating away from the fork. In each region a wave-train is set up with alternate vibrations toward and from the fork, but where these wave-trains meet along lines drawn out from the corners of the fork their vibrations are always in opposite directions and neutralize each other. Along these lines there are accordingly no waves, but the air remains at rest.

(*b*) Bow the Chladni's Plate, and scatter sand upon it to show the lines of no vibration in the plate The plate is seen to vibrate in standing waves and the sand lines represent the nodes. On opposite sides of the sand lines the segments of the plate are accordingly vibrating in opposite directions.

Take a glass funnel of about three inches in diameter and slip a piece of rubber tubing of convenient length over its

stem. Hold the other end of the rubber tubing in the ear, and move the mouth of the funnel about over the vibrating plate and within an inch or so of its surface. When the funnel is held above any one of the vibrating segments the sound of the plate is plainly heard through the tube. When it is held above a node so that as many waves enter it from

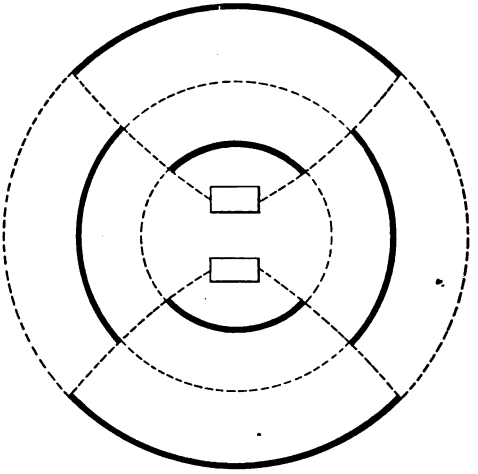


FIG. 64.

one side of the node as from the other, no sound is heard. The two sets of waves which enter the funnel tend to produce vibrations in the opposite direction at the same time and accordingly no vibration is produced. The two sounds are accordingly said to destroy each other by interference.

(*c*) Prepare two resonators from two similar jars or wide-mouthed bottles, and adjust them so that they resound equally well to the same fork. Notice that either resonator will sound to the sides or edges of the fork prongs, but not when the corner of the prong is held above the mouth of the resonator.

Stand one resonator upon the table and hold the vibrating fork above it so that the resonator will sound to the side of the prongs. Hold the other resonator in the hand in a horizontal position so that it may sound to the edges of the

prongs at the same time, as in Fig. 65. The waves which emerge from the two resonators are now vibrating in opposite directions, and will interfere with each other. Hold the fork and resonator in such positions that the sounds issuing from the two resonators may entirely destroy each other. Prove

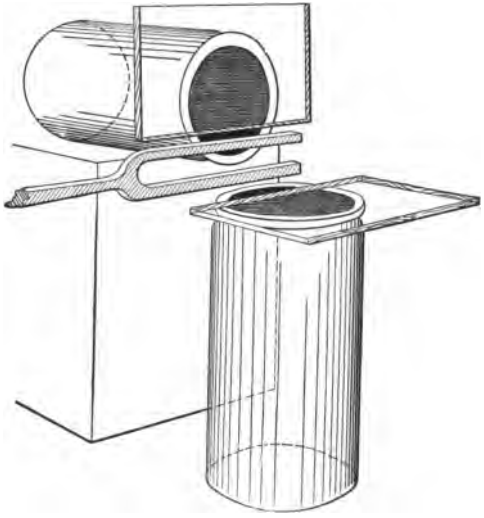


FIG. 65.

that both resonators are sounding all the time by having another person cover the mouth of first one and then the other with a card.*

* It is not true, strictly speaking, that in experiments (*b*) and (*d*) the two sound waves destroy each other. The energy of wave-motion is not decreased, but the waves produced by the vibrating plate and the vibrating tuning fork do not spread out as before.

In the case of the plate, since the segments are vibrating in opposite directions, the air waves in the two halves of the funnel are vibrating in opposite directions, so the air moves up one side of the funnel and down the other at the same time, and the air in the stem is not appreciably affected by this motion.

In the case of the two resonators, the air rushes out of one and into the other and back again, and almost the whole energy of the vibration

(*d*) Hold one of the large mounted forks in the hand with the mouth of its resonance box toward a smooth wall and bow the fork until it sounds loudly. Then move it forward and back, toward and from the wall, and notice the places where the sound of the fork is weakened. These places are where the sound waves reflected from the wall interfere with the waves which the fork is sending off away from the wall. If the fork is at such a distance from the wall that the waves which travel to the wall and back are vibrating in opposite phase to those which start directly from the fork, the two sets of waves will interfere destructively with each other. If the reflected waves fall in with the others in the same phase of vibration, the two sounds will strengthen each other.

Since the two halves of a wave are always in opposite phases of vibration, the reflected waves will interfere with the others when they have traveled a half wave-length farther, or three half wave-lengths, or any odd number of half wave-lengths farther than the others. Since the reflected waves travel to the wall and back again, their path is lengthened by twice the distance that the fork is moved away from the wall. There ought accordingly to be a place of destructive interference for every half wave-length of the sound of the fork as the fork approaches or leaves the wall.

Measure in this way the wave-length of the sound given off by the fork. If the number of vibrations a second of the fork is known, calculate the velocity of sound in air.

Another form of sound interference is shown in the phenomenon of beats.

(*e*) Sound together the two forks used in the resonance experiment. Note that their sounds blend into a smooth note. Slow down the vibrations of one fork by sticking a small weight, as a coin, to one of its prongs by means of a piece of wax, and sound the forks together by bowing them with the violin bow. Notice that their sound is alternately strengthened and weakened, as in the case of the fork moved in front of the wall. The two forks are now said to beat with each other. When the two forks have the same vibra-

is confined to the air in the resonators. If either resonator be covered, the air wave coming out of the other cannot rush into it, and it accordingly spreads out into the surrounding air. The energy of vibration is accordingly as great when the resonators are placed for interference as it was before.

tion period and are sounded together they adjust themselves to each other so that their wave-trains go out in the same phase from both. When the period of the two is slightly different, their wave-trains meet alternately in the same phase and in opposite phase, thus alternately strengthening and weakening each other's sound.

If one fork sends off one wave a second more than the other, their waves will meet in the same phase once a second and in opposite phase once a second.

Change the position of the weight on the prong, and notice the change in the number of beats.

Adjust the forks so that they beat two or three times a second and try the resonance experiment with them. Explain your result.

Beats can be plainly heard in the wires of a piano by raising the damper and striking together a white key and its adjacent black key.

How could you make use of beats in tuning two wires to the same vibration period?

When a church bell sounds, it vibrates in segments, as the Chladni's Plate or the bowed glass vessel used in Exercise 64. Usually on account of irregularities in the thickness of the bell the segments do not all have the same vibration period, hence they produce beats. These beats can be most plainly heard when the sound of the bell is dying out.

Velocity of Wave Propagation.

Laboratory Exercise 71.—Take the free end of the brass spring-cord in the hand and send a wave along it, holding the cord loosely stretched. Repeat, stretching the cord tightly, and notice the difference in the velocity with which the two waves move along the cord. Start a wave in the loose cord, and stretch the cord while the wave is passing along it.

How does the stretching force applied to the cord affect the velocity of wave-motion along it?

The same phenomenon may be observed in standing waves as follows: Fasten a fine silk thread about thirty or forty centimeters long by means of a piece of wax to one prong of a large mounted tuning fork. Carry the thread over a convenient support and attach a weight to the end to keep the thread stretched. Bow the fork as shown in Fig. 66,

so that the thread may vibrate in standing waves. Make the weight heavy enough to cause the vibrating segments to be four or five centimeters long, and place the support so that

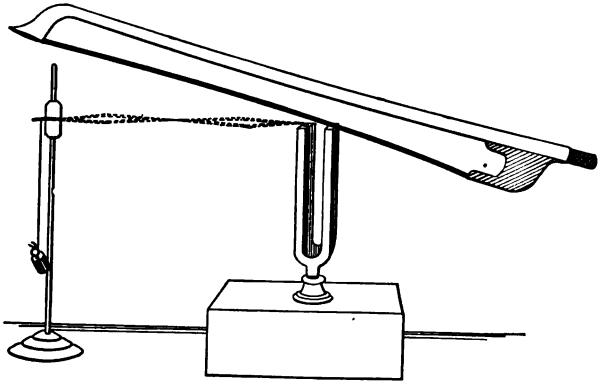


FIG. 66.

there may be two segments between it and the fork, as shown in the figure.

Leaving everything else in position, remove the suspended weight and replace it by one one-fourth as heavy,* and note the length of the standing waves when the fork is made to vibrate.

Replace this weight on the thread by one four times as heavy as the first weight, and note the wave-length as before.

Tabulate your results as follows:

Stretching Force.	No. of Waves.	Wave-length.
1		
4		
16		

*Weights of lead or heavy wire for this experiment should be prepared by the teacher. Their magnitude will depend upon the rapidity of vibration of the fork used.

An electrically driven fork is better for this experiment than one bowed by hand, but the experiment as described offers no difficulties.

How does the number of waves in a given length of thread vary with the stretching force?

How does the wave-length vary with the stretching force?

How does the velocity of wave propagation in a stretched string vary with the stretching force?

In these experiments, the elasticity by means of which the wave is propagated is measured by the stretching force along the cord, since this is the force under which the cord vibrates. We can accordingly use the term elasticity of vibration instead of stretching force in the equations which express the results of our experiments.

Does the equation $v \propto \sqrt{s}$, where v represents wave velocity and s represents the elastic force which causes the vibration, express the results of your experiments?

Leaving the apparatus in position, replace the thread by one made of a piece off the same spool doubled into four strands and lightly twisted. Attach the heaviest weight previously used, and measure the length of the waves in the heavy thread.

How does this wave-length compare with the wave-length of the single thread stretched by the same force?

Is it true to say that the wave-length is decreased as the square root of the weight of the thread is increased?

Does the equation, velocity $\propto \frac{\sqrt{\text{stretching force}}}{\sqrt{\text{weight}}}$, represent the results of your measurements?

What would be the wave-length in the single thread if the stretching force were 25?

What would be the wave length of the heavy thread stretched by a force of 256?

General Equation of Wave-motion.—The formula derived in the preceding experiments for the velocity of wave-motion in stretched cords applies to all elastic bodies by letting e represent the modulus of elasticity of the body, and substituting the density of the body for the weight per unit length of the cord. Thus the

general equation for wave-motion in an elastic medium is $v = \frac{\sqrt{e}}{\sqrt{d}}$, or, as it is frequently written, $v^2 = \frac{e}{d}$.

Water has a density of one and an elasticity of compression about ten thousand times that of air. If the velocity of sound be taken as 338 meters a second in air, what should it be in water?

Relative Velocity of Waves in Air and in Glass.— In the experiment with the glass tube and the cork filings, the waves were set up by the longitudinal vibrations of the glass. Since the tube was clamped at its center, it could not vibrate as a whole, but could only stretch and contract like a piece of India rubber, though on a much smaller scale. This would give the greatest vibration at the ends of the tube, and a place of no vibration at its center. The tube would accordingly vibrate as one half a standing wave, having a node at its center and loops at its ends. The vibration period of the tube is accordingly the period which would give standing waves in glass twice as long as the tube.

The same vibrations produce standing waves in the air in the tube. The wave-length in air for this vibration period is the length of two of the dust segments in the tube. One of the cork-dust segments accordingly represents half a wave-length in air for the same vibration period for which the length of the glass tube represents half a wave-length in glass.

Letting v stand for the velocity of wave-motion in air, v' for the velocity in glass, l for the length of a cork-dust segment, and l' for the length of the tube, we have the equation $v : v' = l : l'$.

This method of comparing the velocities of sound

waves was invented by Prof. Kundt, and the apparatus is known as Kundt's Tube.

Measurement of Relative Velocities of Waves in Air and Glass.

LABORATORY EXERCISE 72.—Measure the relative velocity of a sound wave in air and in glass.

If the density of glass is 2.6 and the density of air .0013, how great is the elasticity of glass as compared with air?

The density of air is doubled by an increase of pressure of one atmosphere; how much would the density of glass be increased by the same increase of pressure?

The velocity of wave-motion in other solids may be measured by using a rod of the substance clamped in the middle and carrying a disc of paper or cork on one end, and inserting this end in the glass tube containing the cork filings. When the rod is set in longitudinal vibration, the disc on its end sets up standing waves in the air in the tube, and the length of these waves is shown by the cork filings, as in the preceding experiment.

NATURE OF SOUND

Two Definitions of Sound.—Thus far we have been concerned chiefly with the physical side of Sound, that is, with the character of the wave-motions which produce the sensation of Sound. It is customary, however, to consider also in a text-book on Physics some of the characteristics of the sensations produced by these vibrations.

Classification of Sounds.—Sounds are usually classified as musical sounds and non-musical sounds or noises. A sound which is produced by a periodic vibration, as the sound of a tuning fork or a violin string, gives a smooth, pleasant sensation, and is called a musical sound. One which is produced by an aperiodic vibration is called a noise. Thus the vibrations which produce wave-trains and standing waves

produce musical sounds, while those which produce irregular waves give the unpleasant sensations called noises.

Limits of Audibility.—All periodic vibrations do not produce musical sounds. When the siren disc is rotated slowly, the puffs of air blown through the hole do not combine to form a continuous sound. The same thing is true in the case of a card held against the teeth of a rotating cog wheel or the spokes of a rotating bicycle wheel. When the wheel rotates slowly, only separate taps are heard, but when the rotation is sufficiently rapid these taps blend into a continuous sound. Experiments have shown that about sixteen vibrations a second are as few as can be combined into a continuous sound. Above that number, the sensation of sound is produced by vibrations up to thirty thousand or more a second. The upper limits of audibility vary considerably in different ears, but about thirty-four thousand a second is considered the maximum number of vibrations which can produce the sensation of sound at all. To greater numbers than these our ears are deaf, and it is not improbable that there are insects which communicate with each other by means of sounds inaudible to the human ear. Certainly there are insects whose notes are above the limits of audibility of some ears, but which can be heard by others.

MUSICAL SOUNDS

Properties of Musical Sounds.—Musical sounds differ from each other in respect to their Intensity, their Pitch, and their Quality.

Intensity.—The Intensity or Loudness of a sound depends upon both the amplitude of vibration and the

surface of vibration of the inducing body. Thus in a given tuning fork the loudness of the sound depends upon the amplitude of vibration of the prongs. When the prongs have nearly come to rest, the sound is very feeble. When the stem of the fork is pressed against the table the sound becomes louder, not because the amplitude of the vibrations of the table are greater than those of the fork, but because the vibrating surface of the table gives its own amplitude of vibration to a large quantity of air in contact with it, while the tuning fork disturbs only a very small quantity of air. When the energy given to the air by each is distributed throughout the surrounding air, the energy of vibration due to the table is much greater at any particular point than that due to the fork.

The intensity of a sound, in the physical sense, is proportional to the energy of the sound wave. The energy of vibration varies as the square of the velocity of the vibrating body. If the vibrations are made in the same time through a long and a short arc, then the velocity of vibration is proportional to the amplitude of vibration. Thus, if a pendulum vibrates in the same time through an arc two centimeters long and an arc one centimeter long, its velocity of vibration is twice as great in the one case as in the other, and its energy of vibration is four times as great in the one case as in the other.

Intensity and Loudness.—The loudness of a sound has reference to the sensation produced by the sound, and it is not known just how this varies with the intensity of the vibrations entering the ear. In general, shrill sounds seem louder in proportion to their physical intensity than do grave sounds.

Variation of Intensity with Distance from Source.—The intensity of a given sound wave at a distance from its source must depend upon the area of the surface to which its energy is distributed. Since in an isotropic medium the sound waves spread out with equal velocity in all directions, giving spherical wave-fronts, the intensity of a given sound wave at any point must depend upon the area of its spherical wave-front at that distance from its source. Since the area of the surface of a sphere increases as the square of its radius, the intensity of a sound wave in an isotropic medium must vary inversely as the square of the distance from its source.

When a wave travels along the spring-cord, its intensity decreases very slowly with the distance from the source, since it is all the time distributed to the same length of cord, and its energy decreases only as it is used up in heating the cord or is given off to the air or the support to which the cord is attached. This explains how sound may be transmitted so far by the string telephone.

In the same way, a wave set up in an isolated column of air loses its intensity very slowly, hence the use of speaking tubes.

Pitch.—The pitch of a musical sound depends upon the rapidity of the vibrations which enter the ear. If the siren disc be rotated rapidly while it is sounding, its note becomes higher in pitch than when the disc is rotated slowly. The same thing is true of a card held against the spokes of a rotating wheel, or of any other vibrating body with variable period.

Doppler's Principle.

LABORATORY EXERCISE 73.—That the pitch of a sound

depends upon the number of waves entering the ear in a given time instead of upon the rapidity of vibration of the sounding body may be shown as follows:

Slip one end of a piece of rubber tubing about a meter long over the mouthpiece of a small whistle, so that the whistle can be sounded by blowing through the tube. Let another person take hold of the tube about its middle and swing the whistle around in a vertical circle while blowing through the tube. Stand so that the whistle alternately approaches you and recedes from you, and listen to its note. You will notice that the pitch of the tone is higher while the whistle is approaching you than while it is receding from you. In the one case a greater number of sound waves enter the ear in a given time than in the other case, since each wave is started from a point a little nearer to you than the previous one, and the waves consequently follow each other closer together than if the whistle were at rest. If the sound waves of the whistle are a foot long and the whistle advances an inch during the time of one vibration, the waves will be induced only eleven inches apart in front of the advancing whistle and thirteen inches apart behind it.

The same difference is noticed in the pitch of a locomotive whistle when the train is approaching you and when it is receding from you.

This dependence of the apparent pitch of a note upon the motion of the sounding body was explained by Doppler in 1842, and is known as Doppler's Principle.

Quality.—The quality of a tone is the property by virtue of which we distinguish the sounds of two musical instruments, as a flute and a violin, or of two voices when they are of the same pitch and loudness.

In general, musical sounds are not of the simple nature of those produced by a vibrating tuning fork, but they are often due to very complex vibrations.

Relation of Quality to Complexity of Sound.

LABORATORY EXERCISE 74.—(*a*) Blow an organ pipe in such a way as to give the lowest sound of which the instru-

ment is capable. This may generally be done by blowing very softly.

Blow harder and see whether you can produce notes of higher pitch.

Blow so that two or more notes can be heard in the pipe at the same time.

The sounds of musical instruments and the sounds of the human voice are usually compound sounds in which two or more simple musical tones can be heard. One of these, usually the lowest, is louder than the others and gives the predominant pitch of the note.

(*b*) That a cord, as a piano wire or a violin string, is capable of transmitting two or more trains of waves at the same time may be shown by setting up a series of long, standing waves in the spring-cord, and then by several properly timed taps on the vibrating cord setting up another series of shorter waves which may be seen running over the loops of the longer waves.

All wind instruments are simply resonators in which the confined air columns are set in sympathetic vibration. We have seen that a resonator may be tuned for any period of vibration, but we have not seen that the same resonator may have more than one natural period of vibration. This is shown as follows:

(*c*) Place the glass resonance tube used in Exercise 68 in its cylinder of water, hold a tuning fork above it, and raise the tube in the water until it resounds to the fork. Mark the length of the tube above the water, and raise it until you have found another length of tube which resounds to the fork. This will be approximately three times the first length.

If the tube is long enough, find a third length of tube in which the air resounds to the fork. If the cylinder is not tall enough for this experiment, take a tube about a meter long and measure the required lengths by pushing a cork along in the tube instead of raising and lowering the tube in water.

When the cork is properly located for reinforcing the sound of the fork, produce a note from the tube by blowing across its open end. Do you get a different note for every different length of tube?

When is the note induced by blowing across the tube the same as the note given by the fork?

These experiments with the tube show that standing waves of different lengths may be set up in the same tube. The number of waves which may be set up is, however, limited by the following considerations:

(α) The closed end of the tube must always be a node, because the air in contact with this end is not free to vibrate.

(β) The open end of the tube must always be a loop, since here is the place where there is greatest freedom of vibration.

The shortest column of air which can vibrate to a tuning fork in a tube closed at one end is accordingly one fourth the wave-length of the sound in air. That is, the tube contains one fourth of a standing wave, with a node at the closed end of the tube and a loop at the open end. Accordingly, any column of air in such a tube can vibrate as one fourth of a standing wave.

The next longer column of air which can vibrate to the same fork is one in which there is a node at the closed end, a loop at the open end, and one node somewhere in the tube. The tube will then be three fourths of a wave-length of the sound to which it is resounding.

By lengthening the tube to take in another node, it becomes five fourths of a wave-length, etc. In the experiments with the Kundt's Tube you saw that the length of a tube may be many wave-lengths of the standing waves set up in it.

(δ) Cut off a tube of the same diameter as the one you have just been using and one half the wave-length of the sound of your fork. The tube is now open at both ends, and should be capable of containing one half of a standing wave produced by the fork, but must have a loop at each end. Since you can have half a wave-length with a loop at each end, the tube should be capable of resounding to your fork. Will it do so?

This tube corresponds to the Kundt's Tube clamped at its center, except that in this case the sound is caused by the vibrating air column, and in the case of the Kundt's Tube it was caused by the vibrating tube itself. In both cases there was a node at the center of the tube and a loop at each end.

Complexity of the Note of an Organ Pipe.—An organ pipe is simply a resonance tube open at one or

both ends, with a mouthpiece so arranged that in blowing through it the air is thrown into vibration by passing over a sharp edge of wood or metal. These waves are of many different lengths. If any of them are of suitable length for setting up standing waves in the tube, they will do so and the tube will strengthen the sound of their particular note. The harder you blow into the mouthpiece, the shorter the waves you produce, and you may blow so hard that there are no waves capable of setting up the lowest note of the pipe. In this case, the pipe may strengthen some note of shorter wave-length.

In general, the pipe strengthens more or less all the notes which are capable of setting up standing waves in it, hence its note is a compound note, instead of a simple note.

Fundamentals and Overtones.—The lowest note which a resonator of any kind can reinforce is called its Fundamental. The higher notes are called Overtones. The Quality of the tone depends upon the relative loudness of the fundamental and the overtones.

Overtones in a Vibrating Wire.

LABORATORY EXERCISE 75.—Stretch a piano wire as in Exercise 64 on a table or a sounding box, and cause it to sound by bowing across its center. In this way you set up standing waves in the wire. From the conditions of the experiment, the wire has a node at each end and a loop in the middle. It is accordingly one half the wave-length of its note. The wave-length is, however, not the wave-length in air, but the wave-length of a transverse wave of that particular vibration period in the particular wire as it is stretched in the experiment.

Since you canot make the wire vibrate as less than half a wave-length, you cannot have a note with longer waves (and consequently with slower vibrations) than the one already

produced. This is the fundamental note of the wire as it is stretched for the experiment.

Touch the wire lightly with one finger exactly at its middle point while you bow it near one end. You will be able in this way to set up standing waves half as long as the others, since by damping the center of the wire you produce a node at that point.

Prove that a node was formed where the finger touched the wire by hanging on the wire a little rider, made of a narrow strip of paper or a bent wire, after the finger has been removed and while the wire is still sounding.

Since the weight and elasticity of the wire remain the same as before, the velocity of wave propagation along it is unchanged. Since $v = n\lambda$, and since v is unchanged and λ is one half as great as before, what change has taken place in n? What change in pitch do you observe to correspond with this difference in vibration period?

Cause the wire to vibrate in three segments by touching it at the place for one node and bowing near the end, as before. Prove by the use of riders that two nodes are formed. How does the number of vibrations which the wire now makes in a second compare with the number made by its fundamental note?

In this way a wire may be made to vibrate in two, three, four, etc., segments, giving a different overtone in each case. This series of overtones is called the Harmonic Series. The first harmonic is the one whose vibration number is twice that of the fundamental; the second, the one whose vibration number is three times that of the fundamental, etc. When a violin string is bowed or a piano wire is struck, some of these overtones are always produced along with the fundamental. The difference in the tone of violins is due to the strengthening of different overtones by the sounding board, or by the resonance of the air in the box.

Overtones in Organ Pipes.

Show by a diagram locating the nodes and loops which overtones of the harmonic series may be produced in an organ pipe open at both ends. In an organ pipe closed at one end.

How long must an open pipe be to give the same fundamental note as a closed pipe two feet long?

PHYSICAL THEORY OF MUSIC

Consonant and Dissonant Tones.—It has long been known that certain tones when sounded together produce a pleasant sensation, while others produce a very unpleasant sensation. Two tones which when sounded together blend with a pleasant sensation are said to be Consonant, while two which produce an unpleasant sensation are said to be Dissonant. On account of this difference in the blending of tones, certain combinations of tones have been chosen for musical instruments and for singing, while other combinations are carefully avoided.

Cause of Dissonance.

LABORATORY EXERCISE 76.—The physical cause of dissonance was first discovered by Helmholtz, and may be understood from the following exercise:

Sound together the two tuning forks which are tuned for resonance. Weight one of the forks so as to give several beats a second, and sound both forks again. By increasing the weight on the one fork, increase the number of beats until they become very rapid, and observe the sensation produced in your ears by the sound of the two forks.

You have seen that as the number of beats in a second increases the dissonance of the two sounds increases. When the number of beats becomes as great as thirty or forty a second the dissonance becomes very great. Helmholtz found that the maximum discomfort was produced by the two sounds when in notes of medium pitch the number of beats is about thirty-two a second. Above that number the beats begin to coalesce into a continuous tone. With notes of higher pitch the maximum dissonance is produced when the beats are still more rapid.

It follows that two tones whose vibration numbers differ by less than thirty or forty vibrations a second are not suitable to be used together in music.

Dissonance of Compound Tones.—We have seen

that most musical instruments, as well as the human voice, give compound tones, and if their overtones are sufficiently loud, beats between them, or between any of them and the fundamental of the other, may cause dissonance. This limits very greatly the number of tones that are suitable for use in vocal or instrumental music.

Musical Scales.—Long before the cause of dissonance was understood musicians had selected a series of tones bearing certain numerical relations to each other in their vibration numbers, and known as a Musical Scale. These tones were selected because they gave less dissonance with each other than other tones in the same range of pitch.

Musical scales have been developed slowly in the history of the race, and differ in different countries at the present time. Certain consonant combinations were recognized in very early times. The best of these was a note and its first harmonic (now called its octave, because six other notes are introduced between them in the musical scale). When these two notes are sounded, there is no sound in the higher tone not also heard in the other. Thus the first harmonic of the higher note is the third harmonic of the lower, the second harmonic of the higher is the sixth of the lower, etc. The two notes accordingly blend so as to produce the best consonance known.

The second best consonance is between a note and the fifth of its octave, that is, between *do* and *sol*. Here the vibration numbers are as two to three. In this combination, the first harmonic of the upper note becomes the second of the lower note, the third of the upper becomes the fifth of the lower, etc.

Musical Instruments.—Musical instruments consist mostly of vibrating strings or wires whose sound is reinforced by the forced vibrations of sounding boards, and of wind instruments in which a partially enclosed column of air is set vibrating by resonance. In wind instruments various devices are used for setting up the vibrations which induce the resonance. In some instruments we have seen this is accomplished by blowing across a sharp edge, in some a small reed is fixed in the mouthpiece of the instrument where it vibrates to the passage of the air as do the reeds of a mouth organ or an accordeon, and in some the lips of the player serve as the vibrating instruments to which the air column resounds.

In the stringed instruments the pitch is determined by the length, weight, and tension of the string, and in instruments like the violin and guitar the pitch of the string is varied while playing by changing its effective length, or by touching it so that it will vibrate in segments and give harmonics of its fundamental tone. In wind instruments the effective length of the air column is changed by various devices, such as opening or closing holes in the sides of the instrument or by opening keys into auxiliary tubes whose length is thus added to that of the original column.

PROBLEMS ON SOUND.—When the velocity of sound is 1100 feet per second, a glass tube 5 feet long and open at both ends resounds to a given tuning fork. What is the rate of the fork?

A brass rod 1 meter long clamped at its middle and provided with a paper disc on one end induces wave segments 10 cm. long in the dust particles of a Kundt's tube. If the velocity of sound in air be taken as 338 meters a second, what is its velocity in brass?

The velocity of sound in brass is .7 its velocity in glass. The density of the glass is 2.5 and that of the brass is 8.5; what are their relative elasticities?

An experiment on the velocity of sound in carbon dioxide gas at atmospheric pressure gave 260 meters a second when the velocity in air was 332 meters. What is the specific gravity of carbon dioxide in terms of air?

PART V

MAGNETISM AND ELECTRICITY

MAGNETISM

PROPERTIES OF MAGNETS

Natural and Artificial Magnets.

LABORATORY EXERCISE 77.—Lay a piece of Lodestone (magnetic iron ore) in a box containing tacks or iron filings. What peculiar property do you observe in the lodestone? Do all parts of the lodestone seem to possess this property to an equal degree?

Try the same experiment with a small bar magnet. With a small horseshoe magnet. In what parts of these artificial magnets does the magnetic property seem to reside?

Try the experiment using small bits of other substances as well as iron and steel. What substances may be attracted by a magnet?

The piece of lodestone used in the experiment is a natural magnet. It is a piece of iron ore of a kind which is found in considerable quantities in various parts of the world, and is often called Magnetite. Its chemical formula is Fe_3O_4. It was formerly found in large quantities about Magnesia, an ancient city near Smyrna in Turkey, and is supposed by some to have received its name from the name of the city.

The bar magnet and the horseshoe magnet are made of steel and are accordingly artificial magnets. The regions about which the magnetic atractions are strongest are called Poles. How many poles has each of the artificial magnets used by you?

Magnetic Poles.

LABORATORY EXERCISE 78.—Lay a knitting-needle on the table and stroke it several times always in the same direction and with the same pole of the horseshoe or bar magnet. Determine if the knitting-needle is made a magnet by this process.

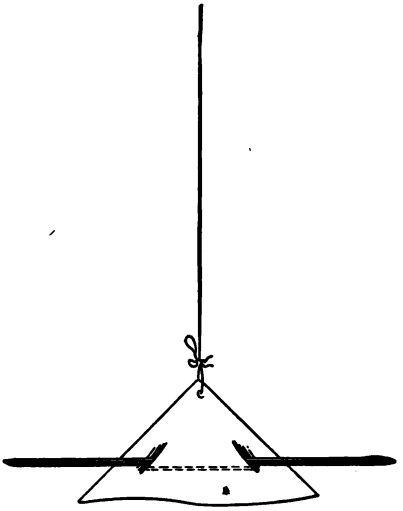


FIG. 67.

Cut out a little triangle of paper, thrust the knitting-needle through it as shown in the figure, and suspend it from one corner by a thread without torsion so that the needle will be supported in a horizontal position. After the needle has come to rest, in what direction does it lie? See that it is not constrained by any twist in the thread.

If the needle always comes to rest in the same position, mark the poles so that you can tell in what direction they pointed, and prepare another knitting-needle magnet and test it in the same way. Call one pole of your magnet its North-seeking pole and the other its South-seeking pole.

Does your bar magnet have North-seeking and South-seeking poles?

Magnetic Attractions and Repulsions.

LABORATORY EXERCISE 79.—Suspend one knitting-needle magnet and holding the other in the hand determine whether there is an attraction or a repulsion between the like and the unlike poles of two magnets. State the law of magnetic attraction and repulsion as follows:

Like poles.....; unlike poles.....

Without suspending the horseshoe magnet determine which is its north-seeking and which its south-seeking pole.

MAGNETIC PERMEABILITY

Magnetic Permeability of Iron.

LABORATORY EXERCISE 80.—Lay a tack on a piece of glass, place a magnet on the other side of the glass and determine if the magnetic attraction acts through the glass. Repeat with wood, paper, and other substances. Substances through which the magnetic attraction acts are said to have magnetic permeability. Do you find any substance not permeable to magnetic attraction?

Hold one pole of a bar magnet against the end of an iron bar a foot or more in length and determine if the magnetic attraction acts through the length of the iron. Which is more permeable to magnetic attraction, iron or wood?

A magnet sealed up in a vacuum can still attract bodies outside, hence the magnetic attraction does not depend upon the existence of intervening matter. Since the magnet may exert an attracting or repelling pressure upon another magnet across a vacuum, this pressure must be transmitted in some medium different from ordinary matter. This medium is supposed to be the same medium which transmits radiation and is called the Luminiferous Ether. The reasons for this supposition will appear later.

The magnetic permeability of the vacuum, that is, of the Ether, is nearly the same as in most bodies, hence it is supposed that the magnetic pressure through these bodies is transmitted by the Ether. Since the permeability of iron is so much greater than of other substances, it is supposed that the Ether is in some way greatly modified in iron.

THE MAGNETIC FIELD

Definition.—The entire region about a magnet in which the magnetic pressure can be shown to exist is called the Magnetic Field. Since the magnetic pressure falls off gradually from the vicinity of a magnet and becomes zero only at an infinite distance, the magnetic field has no definite boundaries. In practice, the magnetic pressure cannot be detected at very great distances from even very powerful magnets.

Magnetic Induction.

LABORATORY EXERCISE 81.—Place a soft-iron bar several inches long with one end very near but not in contact with one pole of a strong magnet. Determine by means of iron filings or small tacks if the iron bar has magnetic poles. Using a suspended magnetic needle, determine the names of these poles. Is the pole nearest to the magnet like or unlike the pole of the magnet nearest to it?

Turn the magnet so that its other pole will be near the end of the bar. Does this change the polarity of the bar?

Remove the magnet. Does the bar still have magnetic poles? If so, are they as strong as before?

A piece of iron placed in the magnetic field becomes itself a magnet. In this case the iron is said to be magnetized by induction. Thus when the north-seeking pole of a magnet is brought near one end of an iron bar, it is customary to say that a south-seeking pole is induced in the end of the bar nearest the magnet and a north-seeking pole in the farther end. In the case of magnetic induction, does the induced pole nearest the magnet tend to attract, or repel, the neighboring magnetic pole?

Do you know of any case of magnetic attraction which is not an attraction between magnets?

Magnetic Force within a Magnet.

LABORATORY EXERCISE 82.—We have seen that when a piece of iron is placed in a magnetic field the magnetic force acts through it to a greater distance than through air, and that in so doing it makes a magnet of the iron. The ques-

tion properly arises whether the magnetic force acts in the same way through a permanent magnet.

File a magnetized knitting-needle or piece of steel spring nearly in two and break it off. Are there magnetic poles at the place of separation?

Break one of the pieces again. Do you cause two more poles to appear? Is there a magnetic force acting lengthwise through the magnet? Can you separate a north-seeking pole and a south-seeking pole so that they will be on different pieces of magnet?

This experiment shows that while the magnetic pressure exists within the magnet, magnetic poles appear only where the magnetic force can be said to pass from the magnet into the air. Accordingly a row of magnets can be put together with their unlike poles in contact and form but one magnet.

All attempts to break a magnet into small enough pieces to separate the poles have failed. Hence it is supposed that the magnetic polarity extends to the molecular structure of the magnet.

THE MAGNETIC CIRCUIT

Relation of Magnetic Poles to Permeability of Medium in Magnetic Field.—We have seen that the magnetic field outside a magnet is continuous with a magnetic field within the magnet. Magnetic poles seem to exist where the magnetic field passes from one medium to another of different permeability. Thus a piece of iron placed in a magnetic field has magnetic poles where the magnetic field enters it and leaves it. In a bar or horseshoe magnet the magnetic field seems to be very weak outside the magnet except near its ends.

Lines of Magnetic Force.

Laboratory Exercise 83.—Place the piece of soft iron, called the "armature" or "keeper," across the ends of a horseshoe magnet. What effect does this have upon the strength of the magnetic field outside the magnet? Does a magnet arranged in this way have poles strong enough to pick up tacks?

Remove the soft iron and test the strength of the poles. What do you conclude in regard to the poles of a magnet making a complete ring?

Before placing the iron across the poles of the magnet, the magnetic field in the air was very strong near the ends of the magnet. With the iron across the poles the field seemed to be confined principally to the magnet itself and to the piece of iron. It is customary to speak of a magnetic field in which no poles are produced as forming a closed circuit within the magnet and the iron. Thus when the two poles of a magnet are joined by a substance of high magnetic permeability the magnetic pressure seems to pass through this substance from one magnetic pole to the other. There is no reason for assuming that this pressure acts in one direction more than in another, but it is customary to speak of the direction in which a north-seeking magnetic pole would be impelled as the positive direction of the magnetic force. A line drawn continuously in the direction in which a north-seeking magnetic pole is impelled is called a line of magnetic force, since such a line shows at every point in its course the direction of the magnetic force.

Since a north-seeking magnetic pole when placed in a magnetic field is repelled by another north-seeking pole, and is attracted by a south-seeking pole, it will move away from the north-seeking pole of the magnet and toward its south-seeking pole. A line of magnetic force would accordingly be drawn everywhere away from the north-seeking pole of the magnet and toward its south-seeking pole.

To Show the Direction of the Lines of Magnetic Force.

Laboratory Exercise 84.—Magnetize a sewing-needle or a piece of knitting-needle about four or five centimeters long. Thrust its north-seeking end in a small cork so that the needle may float vertically in water with its north-seeking pole upward. Rest a strong bar magnet about six inches long horizontally upon two supports just above the surface of water in a vessel, and place the floating needle in the water at a short distance to one side of the magnet. Note the direction in which the needle is impelled.

Here the south-seeking pole of the needle is so much farther from the magnet than its north-seeking pole that the

magnetic force acts principally upon the north-seeking pole of the needle.

Draw lines indicating the direction of the lines of magnetic force in the field near a magnet and farther from the magnet. (Why should this experiment be performed in a vessel free from iron?)

Judging from the velocity of the moving needle in different parts of the field, is the magnetic force stronger near the magnet, or at a distance from it?

We have already seen that we may regard the poles of a magnet as the place where the magnetic force enters or leaves the magnet. Considering the positive direction of the lines of magnetic force, what kind of a pole is produced where the lines of magnetic force enter a piece of iron?

To Trace the Lines of Force by Means of a Magnetic Needle.

LABORATORY EXERCISE 85.—Lay a bar magnet upon the table and by means of a small compass or other mounted magnetic needle determine if one magnet brought into the field of another magnet tends to set itself so that the lines of magnetic force enter at one pole and leave at the other. If so, at which pole do they enter? Show how to draw the direction of the lines of magnetic force by means of the mounted magnetic needle.

Mapping the Lines of Magnetic Force by Means of Iron Filings.

LABORATORY EXERCISE 86.—We have seen that a piece of iron in a magnetic field becomes a magnet with a south-seeking pole where the lines of magnetic force enter it and a north-seeking pole where the lines of magnetic force leave it. If a large number of small pieces of iron are placed near together in a magnetic field they will accordingly become magnets and cling together, the north-seeking pole of one attracting the south-seeking pole of another.

Lay a horseshoe magnet upon the table and lay a piece of stiff paper upon it. Sprinkle iron filings slowly upon the paper from a height of about ten centimeters, and tap the paper gently until they have taken some definite arrangement.

What reason have you for believing that the iron filings are magnetized?

Can you regard a single row of the iron filings as a long, flexible magnet? Why? Does such a row of iron filings lie in the direction of a line of magnetic force?

Sketch the lines of magnetic force about the poles of a horseshoe magnet.

Using iron filings in the same manner, sketch the lines of magnetic force about the poles of a horseshoe magnet with a piece of iron lying near but not in contact with the poles.

By means of iron filings, make sketch maps of the lines of magnetic force about a single bar magnet, about two bar magnets lying side by side with their like poles in the same direction and with their like poles in opposite directions.

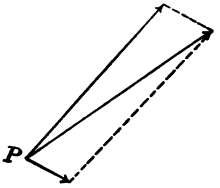
Do the lines of magnetic force ever run from one pole to another pole of the same name?

When do the lines of magnetic force of one magnet pass readily through another magnet?

Theory of Magnetic Curves.—Careful experiments have shown that the attraction or repulsion between two magnetic poles decreases as the square of the distance between them increases. Thus if the attraction or repulsion between two magnetic poles at a distance of one centimeter be n dynes, at a distance of two centimeters it will be $\frac{n}{4}$ dynes, and at a distance of three centimeters it will be $\frac{n}{9}$ dynes.

Make a diagram as in Fig. 68, showing the position of the poles of a bar magnet, and locate a point P twice as far from the south-seeking as from the north-seeking pole of the magnet. Let the point P represent a north-seeking magnetic pole, and assume both poles of the magnet to be equally strong. P will then be repelled by the north-seeking pole of the magnet four times as much as it will be attracted by the south-seeking pole. Draw lines representing the direction and magnitude of the two forces acting upon P, and determine the direction of their resultant.

Make the same determination when P is two thirds as far from the north-seeking as from the south-seeking pole.



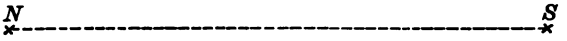


FIG. 68.

How does the direction of the magnetic force as determined above seem to agree with the direction as determined by the other methods?

THE EARTH A MAGNET

The Earth's Magnetic Field.—We have seen that the suspended magnetic needle tends to lie in a direction nearly north and south. If there are horizontal lines of magnetic force about the earth, in what direction do they run?

The Dipping Needle.

LABORATORY EXERCISE 87. — Balance an unmagnetized knitting-needle on a horizontal axis by thrusting it through a piece of cork through which another needle is thrust at right angles to it to serve as an axis. After the needle is carefully balanced magnetize it without changing its position in the cork, and place it parallel to the suspended horizontal needle. Are the lines of magnetic force about the earth horizontal? If not, in what direction do they dip?

The horizontal and the dipping needle indicate that the earth has a magnetic field. If this is true, a piece of iron

placed in the proper position in the earth's field should become a magnet.

Magnetic Induction of the Earth.

LABORATORY EXERCISE 88.—Set the dipping needle so that it points to the magnetic north (The magnetic north may not be the true north), and note the direction of the earth's lines of magnetic force. Hold a bar of very soft iron a foot or more in length at some distance from the magnetic needle and parallel to the earth's lines of magnetic force. Will its end now attract iron filings? Will it repel either end of a compass needle if brought slowly near it?

Holding it still in this direction, strike it several sharp blows on the end with a hammer. Is its magnetic strength increased or diminished by this treatment?

Turn the bar east and west. Is it still a magnet? If so, strike the end as before. How does this affect its magnetization?

See if you can reverse the magnetization of the bar by changing it end for end in the magnetic field without striking it with the hammer. Look for a very small repulsion of the needle.

Write out your reasons for believing the earth to be a magnet.

Magnetic Curves of the Earth.—In latitude about 70° N. and longitude nearly 97° W. the dipping needle stands vertical. This is called the north magnetic pole of the earth. Do the lines of magnetic force enter, or leave the earth at this point? Is it a north-seeking, or a south-seeking magnetic pole? Do you see any objection to calling the north-seeking pole of a magnet its north pole?

The south magnetic pole of the earth has recently been located in 73° 20′ S. latitude and 148° E. longitude. From what we have learned of the magnetic curves of a steel magnet, we should expect a magnetic needle anywhere on the earth to lie with its ends pointing toward these two magnetic poles. This is

not always the case. In many parts of the earth the needle varies considerably from this direction.

MAGNETIC STRENGTH OF FIELD

Definitions.—A unit magnetic pole is defined as one which will repel a similar and equal pole placed at a distance of one centimeter from it in air with a force of one dyne. A magnetic field in which a unit pole would be acted upon by a pressure of one dyne is called a field of unit strength.

It is common in works on magnetism to express the strength of a magnetic field in terms of lines of magnetic force. Hitherto we have used the term "line of magnetic force" to indicate only the direction of the pressure upon a magnetic pole in a magnetic field. It is customary to also give a quantitative value to the line of magnetic force, and to say that a magnetic field of unit strength is one which has one line of magnetic force to the square centimeter.

A field which exerts a pressure of 10 dynes on a unit magnetic pole is said to have a field strength of 10 lines to the square centimeter, and the like. This is an unfortunate method of expressing the intensity of magnetic action, since there is no reason for believing that certain parts of the Ether in the magnetic field differ in their properties from other parts.

The high magnetic permeability of iron is expressed in terms of lines of force by saying that iron is a better carrier of lines of force than air. Thus the magnetic field induced through iron by a magnet is many times as strong as the field induced through air at the same distance from the magnet. Iron is accordingly said to

permit the passage of many more lines of force than air for the same magnetic pressure.

Questions on Magnetism.

A compass is placed at some distance from one of the poles of a bar magnet. Will the action of the magnet upon the compass needle be increased or diminished by placing a piece of soft iron between it and the magnet but not in contact with the magnet? Why?

A compass is placed at an equal distance from both poles of a horseshoe magnet; will the directive action of the magnet be increased or diminished by placing a single piece of iron between it and both magnetic poles? Why?

A compass is placed in a magnetic field and is surrounded by a cylinder of iron. Is the influence of the magnetic field upon the compass increased or diminished by the iron? Explain?

Will the works of a watch in an iron case be more or less liable to become magnetized than in a case of some other metal?

Will a magnetic needle floated on a cork in water tend to move toward the north magnetic pole of the earth? Why?

ELECTROSTATICS

ELECTRIFICATION

Electrification of Sealing Wax and Glass.

LABORATORY EXERCISE 89.—Suspend a light body, as a pith ball, an egg shell, or a paper cylinder by a thread a foot or more in length. Rub a clean, dry stick of sealing wax gently with a piece of warm, dry, woolen cloth, or brush it with fur, a feather duster, or a clothes brush not made of vegetable fiber. Bring the rubbed end of the sealing wax near the suspended body and observe if a force is exerted between them. If so, the sealing wax is Electrified.

See if the electrified sealing wax can be made to attract other light bodies. Balance a meter stick or a long board on the round top of a glass bottle stopper or other suitable support and see if you can cause it to rotate by the attraction of the electrified sealing wax.

Instead of the sealing wax, use a clean, dry glass rod or piece of glass tubing whipped or gently rubbed with a piece of silk.* Is the glass electrified? Can you electrify it as strongly with the woolen as with the silk?

Try to electrify hard rubber, sulphur, rubber tubing, porcelain, metal, wood. Which ones can you electrify? Does it make a difference which material is used as a rubber?

Origin of Name Electrification.—The phenomenon of electric attraction was known to the Greeks at least 2500 years ago. It was first discovered in rubbed amber, and was explained by Thales, B.C. 580, by attributing to amber a kind of life. The Greek word for amber is *Elektron*, and this condition of rubbed amber came to be called Electrification. The amber or sealing wax when in this condition is said to be Electrified, or to have an Electric Charge.

Electrics and Non-electrics.—This was practically all that was known of electrification for more than 2000 years. In the year 1600, Dr. William Gilbert, physician to Queen Elizabeth, of England, published the fact that many other bodies besides amber are capable of electrification. He classified bodies as Electrics and Non-electrics, according as he found them capable or incapable of being electrified.

Electric Repulsion.

LABORATORY EXERCISE 90.—Electrify, as before, one end of a stick of sealing wax, and taking care not to touch the electrified part, suspend it horizontally in a stirrup made of bent tin or wire and supported by a string a foot or more long. A piece of very narrow silk ribbon ("baby" ribbon)

* All the materials used in the experiments on static electricity must be kept very clean and dry. In moist weather they must be warmer than the air in the room and must not be handled on the parts which it is wished to electrify. They may be cleared from grease by washing with gasoline on a clean cloth.

makes an excellent supporting string, as it has no torsion, and will be found useful in later experiments.

Hold the finger near the electrified end of the sealing wax. Does the finger attract the sealing wax? Would this necessarily follow from what you know about force? Robert Boyle announced this as a discovery in 1675. Which one

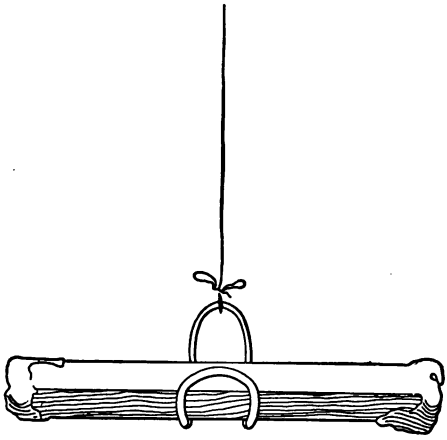


FIG. 69.

of Newton's Laws of Motion was not comprehended by Boyle?

Electrify another stick of sealing wax, and bring its electrified end near the electrified end of the suspended sealing wax. Make sure that the suspended sealing wax has not lost its electrification. What kind of a force is exerted between two similarly electrified bodies?

The phenomenon of electric repulsion was discovered by Otto von Guericke, of Magdeburg. What important invention do we owe to von Guericke?

Will a glass rod electrified by silk attract or repel the electrified sealing wax?

Suspend a glass rod electrified by silk and see if it is repelled by another glass rod similarly electrified.

Find whether a piece of sulphur electrified by woolen is electrified like the sealing wax or like the glass.

What is the character of the electric force between similarly electrified bodies? Between dissimilarly electrified bodies? Where have you seen analogous forces?

Two Kinds of Electrification.—Bodies electrified like glass rubbed with silk are said to be "Vitreously" electrified, or to have "Vitreous electrification." Bodies electrified like sealing wax rubbed with wool or fur are said to have "Resinous electrification." Since all electrified bodies will repel either the electrified glass or the electrified sealing wax, we know of only these two kinds of electrification. (Why may we not test the character of electrification by attractions instead of repulsions?)

Transference of Electrification by Contact.

LABORATORY EXERCISE 91.—Suspend a light pith ball* by a dry silk thread one or two feet in length. (The thread should not be drawn through the hand or over any unclean surface.) Bring an electrified stick of sealing wax near enough that the pith ball may be drawn to it and come in contact with it. Does the pith ball receive electrification from the sealing wax? Does the sealing wax lose all or only a part of its electrification to the ball?

Bring a similarly suspended pith ball near the first one and allow them to be drawn together. Is the electrification now divided between them? Do the pith balls have vitreous or resinous electrification?

Opposite Character of Two Kinds of Electrification.

LABORATORY EXERCISE 92.—Electrify one of the suspended pith balls from glass and the other from sealing wax and then allow them to come in contact with each other. Is their electrification strengthened or weakened by the contact? What is the character of the charge, if any, on each after

*Pith balls suitable for these experiments may be made from the dried pith of various vegetable stems. Sunflower pith is especially adapted to this purpose. The balls should be cut out with a sharp knife, and should be smoothed by gently rolling them between the hands.

contact? Can you so electrify the two balls that after contact neither of them will be electrified? Can you so electrify them that after contact both will have resinous charges?

Use of Terms Positive and Negative.—We have seen reasons for the belief that the two kinds of electrification represent opposite conditions of the electrified body, and this opposite character has been expressed by the terms positive and negative. Just as the algebraic addition of numerically equal, positive, and negative quantities produces zero, so the addition of so-called equal quantities of vitreous and resinous electrification produces zero electrification.

There is no known reason for regarding one kind of electrification as positive rather than the other; but by general agreement the vitreous electrification has been called positive and the resinous negative. These two kinds of electrification are accordingly marked with the signs + and − just as are the algebraic quantities.

Simultaneous Production of Both Kinds of Electrification.

Laboratory Exercise 93.—Suspend the two pith balls at a distance of a foot or more apart and electrify them oppositely. Take a small piece of flannel attached to a handle of sealing wax by sticking it to the wax or sewing it around the end of the stick, and holding to the sealing-wax handle, rub another stick of sealing wax with the flannel. Is the sealing wax electrified as usual? Is the flannel also electrified? If so, what is the character of its electrification?

With a piece of silk attached in the same way to a sealing-wax handle, electrify a glass rod. Is the silk also electrified? If so, what is the character of its electrification? (Take care that the sealing-wax handles to which the silk and flannel are attached are not electrified.)

Try to electrify the pieces of silk and flannel by rubbing them together. Give results. Are both kinds of electrification produced at the same time?

The Electrostatic Series. — The four substances which you have used to produce electrification may be arranged in a series such that when any two are rubbed together the one higher on the list will be positively electrified and the one lower on the list negatively electrified.*

This series is called the Electrostatic Series. The following substances are arranged in such a series: Fur, Flannel, Feathers, Quartz, Glass, Cotton, Linen, Silk, Wood, Metals, Sulphur.

What would be the character of the electrification produced on quartz by rubbing it with fur? With silk? Do your experiments on the electrification of glass justify its position between flannel and silk in the series?

The experiments which follow are best performed by means of an electric machine, though in a favorable climate they may all be performed without one. The principles involved in the construction of the electric machine are not discussed here, since several different kinds of electrical machines are used.† At present it will be regarded as an instrument for producing readily an electrification of either kind desired. For this purpose the electric machine should be charged and the character of the electrification of its discharging knobs should be tested by means of the charged pith ball.

ELECTRIC CONDUCTION

Conductors and Non-conductors.

LABORATORY EXERCISE 94.—Place a convenient body of wood or metal on a glass support (a potato resting on a

* Owing to differences in glass, the relative positions of glass and flannel are sometimes uncertain.

† The teacher should explain the machine he uses when in his opinion his class is prepared for it.

glass tumbler or beaker is as good as anything), and attach to it a pith ball or cork suspended by a short linen thread so that it will hang in contact with the body. Lay a wire from one discharging knob of the electric machine to the body, and try whether you can electrify the body from the machine. Bodies which allow electrification to pass along them are called conductors. Test and classify as conductors and non-conductors glass, sealing wax, rubber, silk, wood, metals, threads of different kinds, etc.

Why were your pith balls in former experiments suspended by silk threads? Why should these threads be dry? Why is the body used in these experiments mounted upon a glass support? Why were the pieces of silk and flannel mounted on sealing wax? Why did Dr. Gilbert fail to electrify his "non-electric" substances when held in his hand? What new classification can you substitute for electrics and non-electrics?

Insulators.—Non-conducting bodies are also called Insulators, because they must be interposed between electrified conducting bodies and the earth if these bodies are to retain their electrification. No body is a perfect insulator, but some bodies allow electrification to escape very slowly. In the experiments which follow where perfect insulation is desired a block of hard paraffin or sealing wax or a silk thread or ribbon support will serve the best. The success of all electrical experiments depends upon careful insulation of all charged bodies. Glass is frequently a very poor insulator, and frequently a conducting layer of moisture gathers on its surface. Its insulating properties are often improved by washing with gasoline. The successful working of an electric machine depends upon the careful insulating of the different parts, and many good machines are discarded when they need only a careful cleaning and drying.

ELECTROSTATIC INDUCTION

Electrification by Induction.

LABORATORY EXERCISE 95.—Suspend two pith-ball pendulums or other light conductors by silk threads about 10 centimeters long and about 10 centimeters apart, and lay a fine wire long enough to reach from one to the other lightly upon them. Bring an electrified stick of sealing wax or a

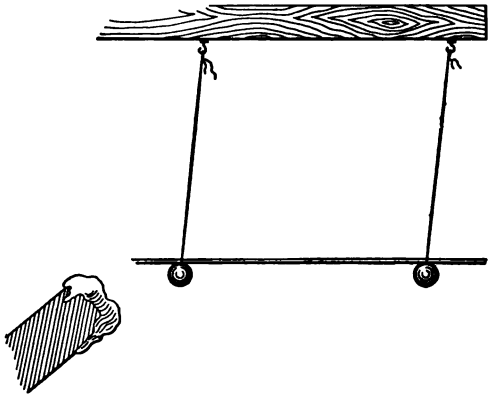


FIG. 70.

conductor electrified by the machine near enough to one pendulum to attract the pendulum and cause the wire to fall off, but do not let the charged body touch the pendulum.

Remove the electrified body, and test both pendulums for electrification. Are they similarly or oppositely electrified? How does the electrification on the one nearest the charged body compare with the electrification of the body? To what phenomenon in magnetism is electrostatic induction comparable?

Bring an electrified body near a silk suspended pith ball, and while holding it in this position touch the pith ball with your hand. Remove the hand and then the charged body. Is the pith ball electrified? How does the character of its electrification compare with that of the inducing charge? What was the purpose of touching the ball with the hand? How can you electrify several bodies from a single electrified

body without decreasing the original charge? Will they be electrified like or unlike the original charge?

Equality of Induced + and − Charges.—You have seen that an electrified body brought near an insulated conductor induces both positive and negative electrification upon the conductor. If the charged body be removed before either kind of electrification is allowed to escape from the conductor, it will show no charge; hence the two kinds of electrification must be induced in quantities just sufficient to neutralize each other. We accordingly call these quantities equal in magnitude.

Maxwell says:* "*No force, either of attraction or repulsion, can be observed between an electrified body and a body not electrified.*" How can you harmonize this statement with the observations upon electric attraction and repulsion which you have made?

The Electrophorus.—A cake of some non-conducting substance, as sealing wax or paraffin, may be electrified by brushing it with wool or fur, and may then be used to electrify by means of induction an insulated metal plate. This instrument is called an Electrophorus. Thus a cake of hard paraffin is melted and allowed to cool on a tin plate. It is then electrified, and a metal disc or smaller tin plate with an insulating handle is placed flat upon it. On account of the uneven surface of the paraffin the metal will

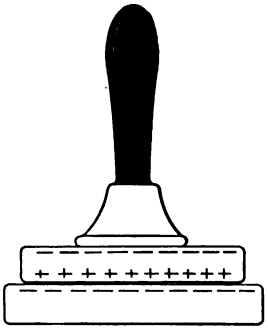


FIG. 71.

* Electricity and Magnetism, Vol. I, p. 33.

touch it at only a few points, and will not carry off much of its electrification. Fig. 71 indicates the distribution of the electrification on the metal plate at this stage of the experiment. If now the metal be touched by the hand and then raised by its insulating handle it will be found highly electrified, and may be used instead of an electric machine for charging other bodies. It may be charged in this way many times without perceptibly weakening the charge on the paraffin.

The Bound Charge.—You have seen that it is impossible to remove the negative electrification induced by a positive charge, or *vice versa*, by touching it with the hand while the inducing charge remains near it. When the inducing charge is withdrawn the induced electrification is readily removed. The induced charge is accordingly said to be bound by the inducing charge.

Since there are always conductors in the vicinity of a charged body, there are always bound charges upon these conductors. Every electrified body is accordingly surrounded by oppositely electrified bodies.

THE ELECTRIC FIELD

Electric Attraction and Repulsion Due to the Medium Surrounding the Charge.—We have seen that an electrified body is capable of exerting a pressure upon another electrified body brought near it. The region in which this pressure can be observed is called the Electric Field.

Since any electrified body induces a bound charge upon conductors surrounding it, the electric field is always bounded by positive and negative charges. Within this field a positively electrified body is always impelled from the positive to the negative charge, and

a negatively electrified body from the negative to the positive charge. This tendency to movement is due to some kind of a pressure exerted upon the electrified body by the medium of which the electric field is composed.

The Dielectric and Electric Elasticity. — The medium which constitutes the electric field and which is bounded by the two opposite electrifications is called the Dielectric. Since the electric pressure resembles the pressure exerted by elastic substances, Maxwell has called the property of the dielectric by means of which it exerts a pressure upon electrified bodies its Electric Elasticity.

The Luminiferous Ether a Dielectric.—Since the electric pressure is exerted in a vacuum as well as in air, the vacuum must have electric elasticity. The only known medium existing in the vacuum is the Luminiferous Ether, and we shall later see the best of reasons for believing that the electric pressure is due to the Luminiferous Ether, and that the Ether may become a dielectric.

Lines of Electric Force.—The electric field is accordingly a condition set up in the dielectric. This condition is such that a positively electrified body is impelled in one direction and a negatively electrified body in the opposite direction. The electric field, like the magnetic field, may accordingly be said to have lines of force. The direction in which a positively electrified body is impelled is called the positive direction of the lines of electric force. Where the lines of electric force leave a conductor we have the condition known as positive electrification. Where they enter a conductor, we have negative electrification. An insulated conductor placed

in the electric field has positive electrification on one side and negative electrification on the other, just as a piece of iron placed in the magnetic field has a north-seeking pole on one side and a south-seeking pole on the other. When a conductor in the electric field is in electric communication with the earth its lines of electric force on one side run along the conductor to or from the earth and only the electrification of the bound charge appears upon the conductor. Thus if the earth were made of iron, or if its magnetic permeability were as great as that of iron, a piece of iron in a magnetic field and in contact with the earth would show only one magnetic pole.

To Show the Effect of Surrounding Conductors upon the Electric Field.

LABORATORY EXERCISE 96.—A thin metal plate, as a piece of tin or sheet copper, has its edges and corners carefully rounded off with a file and is supported vertically by some insulating material. It may be suspended by two silk ribbons, or mounted on hard rubber, sealing wax, or paraffin. Attach two similar pith or cork balls to opposite sides of the plate by short linen threads so that they will hang against the plate. Remove all other conductors to some distance from the plate and electrify it until the pendulums stand out to some distance from the plate. Note that they are repelled equally on both sides. This indicates that the electric field is the same on both sides of the plate.

Bring a similarly insulated unelectrified plate with pith-ball pendulums near on one side and notice that the electric field passes through the second plate without greatly affecting the distribution of the field about the first plate. Bring the second plate in communication with the earth by touching it with the finger. Does the electric field now pass through it? What change has occurred in the distribution of the field about the electrified plate?

Holding the finger against the second plate, bring it nearer to the electrified plate. The pith balls now take the posi-

tions shown in Fig. 72. Is the electric field drawn in between the two plates or driven out from between them? Is the bound charge increased or diminished upon the second plate? Are the bound charges upon distant conductors increased or diminished? How can you tell?

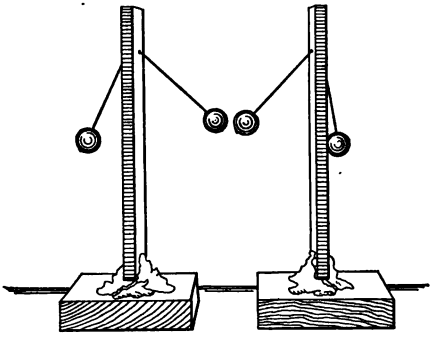


FIG. 72.

Electric Condensers.—An arrangement of conductors by means of which the field of an electrified body is confined to a small region of the dielectric is called a Condenser. Can you make the two plates serve as a condenser? How can you screen an unelectrified body from the influence of an electrified body near it?

The Electric Field of the Leyden Jar.—The Leyden Jar is made by coating the inside and outside of an insulating glass jar with tin-foil (which is pasted to the glass), to about one half the height of the jar. To improve the insulation of the glass above the tin-foil it is usually thinly coated with shellac from an alcohol solution. A wire with a knob at the top is passed through a wooden cover, and by means of a piece of chain or fine wire is brought in contact with the inner coating of tin-foil. The jar is electrified by bringing the knob in contact with the discharging knob of an

electric machine while the outer coating of the jar is in electric communication with the earth. The bound charge is then upon the outer coating of the jar, and the glass between the two coats becomes the dielectric.

Energy of Electric Field in the Dielectric.

LABORATORY EXERCISE 97.—Take a small glass beaker or wide-mouthed bottle which is found to insulate well. Fill it half full of shot to serve as the inner conductor, and stick a nail in the shot to receive the charge from the electric machine. Hold the beaker tightly in the hand, being careful to leave a large insulating surface above the hand. The

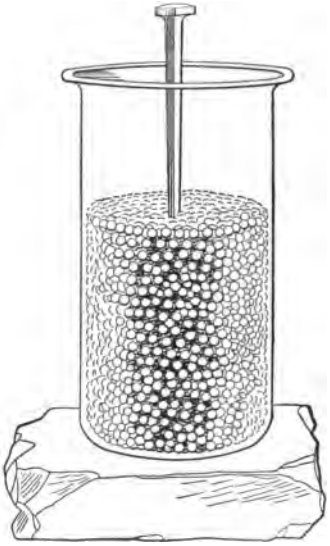


FIG. 73.

beaker is then a condenser with the glass for the dielectric and the hand as the conductor upon which the bound charge will be held. Holding the beaker near the machine, allow a few short sparks to pass to the nail. Then touch the nail with the finger of the other hand. If no effect is felt upon touching the nail, pass more sparks to it and try again.

When a slight shock is felt upon touching the nail, the condenser is sufficiently charged. Charge the condenser as before, sufficiently high to give an appreciable shock. Set it upon a block of paraffin, as shown in Fig. 73, remove the hand from the outside of the beaker, and then withdraw the nail. Why do you feel no indications of the discharge? Have the bound charges changed places in the condenser?

Pick up the beaker, pour out the shot and set it back upon the paraffin block. Pour in as much shot from another vessel, replace the nail, grasp the outside of the beaker tightly in the hand and touch the nail with the other hand. If you feel no evidence of the discharge, repeat the experiment, charging the shot more highly.

Can you show that the energy of the electric field is in the dielectric and not in the conductors?

Electric Field of a Hollow Conductor.

Laboratory Exercise 98.—Set a deep tin cup, a tin can from which all the rough edges have been removed, or a hollow wire conductor such as is often sold for a fly trap, on a block of paraffin, or suspend it by insulating strings. Attach two pith balls to the ends of a linen thread long enough that they can be suspended over the edge or through the meshes of the conductor, one hanging inside and one outside and reaching nearly to the bottom of the conductor. Suspend the two balls so that they will rest against the same side of the vessel and opposite each other. Electrify the conductor from the machine. Is there evidence of an electric field on the inside? Hold another conductor in the hand and move it about near the charged hollow conductor on the outside. Can you change the distribution of the electric field on the outside? Why should there be no electric field on the inside?

Try to charge a metal ball attached to a silk thread by lowering it into the hollow conductor and allowing it to touch the side near the bottom. Can you charge a body by contact when it is not in an electric field?

Discharge the hollow conductor and lower a charged metal ball attached to a silk thread into it, taking care that the charged ball does not touch the sides of the hollow conductor (see Fig. 74). Is there now an electric field inside the hollow conductor? Is there an electric field on the outside?

Where is the bound charge induced by the charged ball? To what is the field on the outside of the hollow conductor due? If the ball is positively charged, what is the character of the charge on the outside of the hollow conductor? Touch with the finger the outside of the hollow conductor.

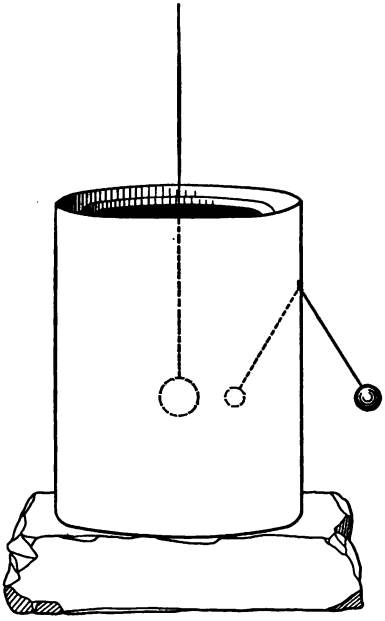


FIG. 74.

Can you destroy its electric field on the outside? Is there still an electric field on the inside?

Withdraw the charged ball without allowing it to touch the outer conductor. Does the hollow conductor now have a field on its outside? What is the nature of its electrification? To what is it due?

Discharge the hollow conductor and lower the charged ball into it again. Does the electric field appear again upon the outside?

Let the charged ball come in contact with the hollow

conductor on the inside. Which electric field now disappears? Tell by observing the attached pith ball if there is any noticeable change in the strength of the outside field.

Withdraw the ball and test it for electrification. Where is the electric field which was around the ball when it was lowered into the hollow conductor? Is the field apparently of the same strength as when it belonged to the ball?

Was the bound charge in the inside of the hollow conductor exactly equal in magnitude to the inducing charge upon the ball? How can you tell? Where is now the bound charge?

How can you make one conductor give up its entire charge to another?

The pith balls which you have used for the detection of electrification are often called electroscopes, that is, electric indicators. Much more sensitive electroscopes may be devised, but the most sensitive electroscope attached to the hollow conductor fails to show any change in its electrical field when the charged ball on the inside is allowed to touch it.

Mapping the Lines of Electric Force.—The Electric Field, like the Magnetic Field, may be mapped out by using particles of some feebly conducting substance instead of the iron filings used in the magnetic field. The experiment would better be performed by the teacher.

Pour enough turpentine oil in a flat-bottomed glass vessel to cover the bottom to a depth of half a centimeter. Place two pieces of metal at a distance of eight or ten centimeters apart in the oil, and connect them to the knobs of the electric machine. Let one person turn the machine slowly, not fast enough to cause currents in the liquid, while another holds a piece of colored crayon above the liquid and files off coarse particles with a rough file. By turning the machine at the proper rate and distributing the particles evenly in the liquid they will form connecting lines between the

two pieces of metal like the lines of iron filings between the magnetic poles. In this case, the chalk filings are turned into position by the attraction between their induced charges.

Fig. 75 is made by mapping an electric field with chalk filings in a glass vessel standing on a photographic plate in a dark room. After the machine was disconnected, a lighted match was held above the vessel, causing its shadow to be projected upon the photographic plate and the plate was developed.

The round spots show the position of the metal cylinders which were connected to the knobs of the electric machine, and the rectangular dark spot shows the position of a piece of brass which was placed in the liquid but was not connected with the electric machine.

Compare with the map of a magnetic field in which a piece of iron is placed near the magnetic poles.

Electric Potential.—On page 44 we used the term "Potential" of a point in space to indicate the potential energy which a unit mass would have at that point on account of gravitation. Since two electrified bodies brought near each other have potential energy on account of the electric pressure tending to separate them or bring them together, we may calculate the *electric potential* of a point in space as well as its *gravitation potential*. If we agree upon a unit quantity of electrification, we may say that the electric potential of a point in space is the measure of the potential energy which the unit quantity of electrification would have at that point. In this view, what we have called the electric pressure corresponds to the gravitation pressure or the weight of the unit mass in gravitation potential.

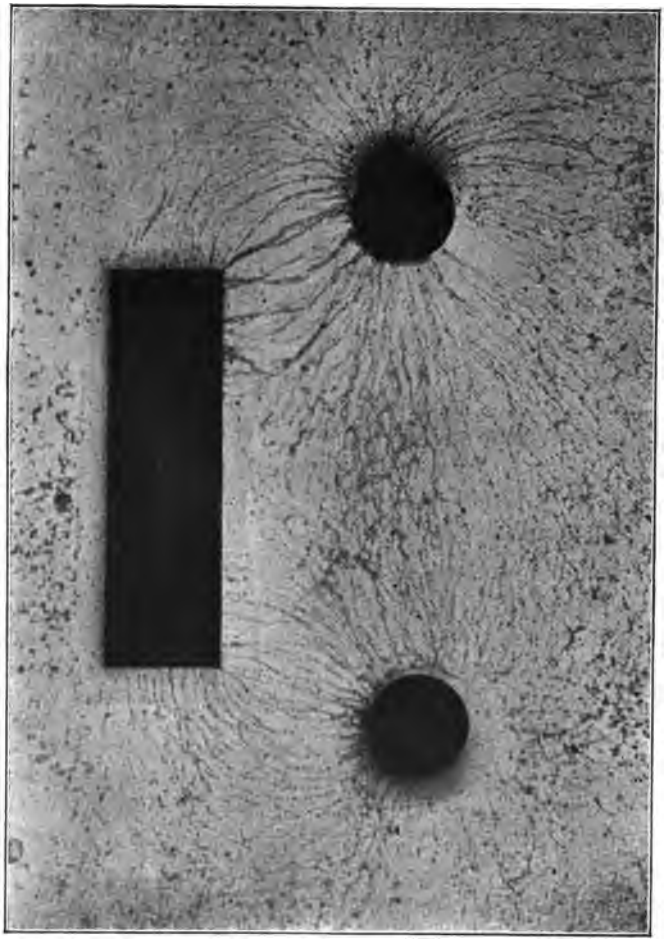


FIG. 75.

Since a positively electrified body will be driven in one direction in an electric field and a negatively electrified body will be driven in the opposite direction, a point in an electric field may have a different potential for the two kinds of electrification. It is accordingly customary to regard the electric potential of a point as the potential energy which the unit quantity of positive electrification would have at the point due to the repulsion of the electric field upon it.

Since a positively electrified body would not be repelled in the field of a negatively electrified body it would have no potential energy due to repulsion in such a field, but would require the expenditure of work upon it to carry it away from the negatively electrified body; hence its potential is said to be negative.

Zero Potential.—Since all electrified bodies lose their electrification on contact with the earth, the earth is regarded as unelectrified, and hence at zero potential.

Potential Difference.—It is sometimes possible to calculate the electric potential of a point in space, but the problem is principally of mathematical interest. What we generally wish to know in practice is the potential difference between two points. The potential difference of two points is the measure of the work which must be done on a body charged with the unit quantity of positive electrification to carry it from the one point to the other.

Since work is measured by force into distance, or $W = FS$, the potential difference between two points will be greater the greater the electric force between them. Thus if $V - V'$ represent the potential difference between two points and S the distance between

them, $\frac{V - V'}{S} = F$, where F is the *average* electric force between the points. The average electric force between two points is accordingly the change of potential per unit distance between the two points.

Electromotive Force. — Electromotive Force is a name given to whatever tends to move an electric charge. In the proper sense it is not a force at all, because force has been defined since the time of Newton as whatever produces or tends to produce an acceleration in a material body. An electromotive force does not affect a material body at all, hence cannot produce an acceleration in such a body. It does, however, produce an acceleration of an electric quantity, and hence is analogous to a force, just as the electric elasticity of a dielectric is analogous to the elasticity of a material body.

The best-known form of electromotive force is the pressure which is exerted upon an electric charge in an electric field. This form of electromotive force may be measured, as above, by the potential difference between the two charges divided by their distance; that is, E.M.F. $= \frac{V - V'}{S}$.

ELECTRIC QUANTITY

Definition of Unit Quantity.—We have spoken of a unit quantity of electrification, but have not defined it. It has been defined as the quantity which at a distance of one centimeter from a similar and equal quantity would be acted upon by a pressure of one dyne. The electrostatic unit of quantity is accordingly very small, and is not used at all in practical work.

ELECTRIC CAPACITY

Definition of Electric Capacity.—When two electrified conductors come in contact with each other the electric pressure becomes the same over the surface of both. Since there is no difference of electric pressure between the two bodies, there can be no difference of potential between two points on their surfaces, hence the bodies are said to be charged to the same potential.

We have seen that a small body, as a pith ball, may be charged by contact to the same potential as a larger body without appreciably decreasing the electrification of the larger body. We accordingly see that different quantities of electrification may be required to charge different conductors to the same potential. This is expressed by saying that different conductors have different electrical capacities. A large sphere has a greater capacity than a small sphere. The capacity of a conductor is measured by the quantity of the charge which must be given to it to raise its potential from zero to unity. Thus if C stand for capacity, Q for quantity of charge, and V for potential, $CV = Q$.

Capacity of a Condenser.

LABORATORY EXERCISE 99.—Set a Leyden Jar upon a block of paraffin or other insulating support and connect its knob to one knob of the electric machine. Separate the knobs of the machine a few millimeters and turn the handle, noting the time between the sparks. When the difference of potential between the knobs becomes great enough, the dielectric between them is broken through and the knobs are discharged by a spark. For the purpose of the present experiment, it may be assumed that the "Electric Strength" of the dielectric is constant, and that a spark will pass under the same difference of potential each time. Does this seem to be approximately true?

Now remove the insulating block, or connect the outer coating of the Leyden Jar to earth by a conductor, and turn the machine at the same rate as before. What effect does this have upon the time between sparks? What effect upon the character of the spark? What effect has connecting the outer coating of the jar to earth had upon the electrical capacity of the inner coating of the jar?

SPECIFIC INDUCTIVE CAPACITY

Experiment on Specific Inductive Capacity of Paraffin.

LABORATORY EXERCISE 100.—Two metal discs are connected by a conducting rod, and are mounted upon an *insulating* support. One of the discs is provided with a pith-ball pendulum to serve as an electroscope.

Two other metal discs of the same size as those mounted upon the rod are placed at a distance of an inch or two from the first ones, and are mounted upon *conducting* supports or connected to earth.*

Charge the insulated discs until the pendulum stands out as shown in Fig. 76. You now have two similar condensers at the ends of the insulated rod. Support a block of paraffin as large as the discs and of a thickness nearly equal to the distance between the condenser plates by a narrow silk ribbon or thread attached to two of its corners, and after passing the hand over its faces to remove any charge which may be on them lower it into one of the condensers as shown in the figure, meanwhile noticing the movement of the pith-ball pendulum in the other condenser. Withdraw the paraffin block, and repeat the experiment until you are certain what effect its introduction has on the other condenser.

Discharge the condensers and introduce the paraffin as before to determine whether it carries an electric charge. If it is found to be charged, discharge it by passing it quickly through a flame, and when it is completely discharged repeat the whole experiment.

Since the insulated discs of the condensers are joined by

* A tin can, as a baking-powder can, mounted upon insulating supports may take the place of the rod and discs, and two other can covers mounted upon wooden supports may serve for the movable discs.

a conductor, they must remain always at the same potential. Since the other discs are joined to earth, they must be always at zero potential. The potential difference in the two condensers must accordingly remain the same throughout the experiment.

Is this potential difference increased or diminished by the introduction of the paraffin? (If it is increased, the

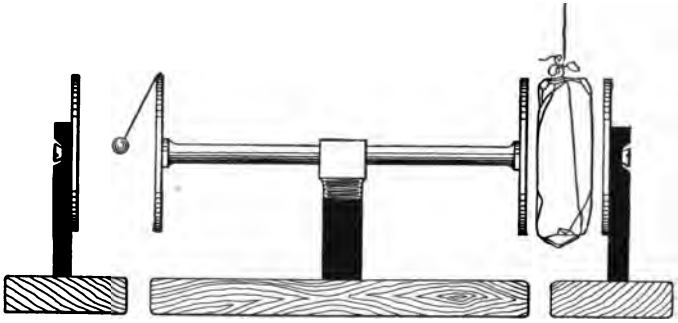


FIG. 76.

electric field in both condensers is strengthened, and the pith ball is more strongly electrified than before.)

When the paraffin is introduced, must the charge of the insulated discs be increased or diminished to restore the previous strength of field in the condensers?

Is the capacity of the paraffin condenser greater or less than that of the air condenser?

Is the introduction of the paraffin equivalent to separating the plates or to bringing them together? Try the experiment.

Is the bound charge induced through paraffin greater or less than that induced through the same thickness of air?

Definition of Specific Inductive Capacity.—The fact that electric induction takes place more readily through some dielectrics than through others was discovered by Faraday, who gave the name Specific Inductive Capacity to that property of dielectrics by means of which induction is produced. Substances through which induction takes place easily are said to have a

high specific inductive capacity, or a high "Dielectric Capacity." The specific inductive capacity of a conductor is so great that induction takes place through it as readily as if the condenser plates were moved nearer together by the thickness of the conductor.

Relation of Specific Inductive Capacity to Electric Elasticity.—We have seen that increasing the specific inductive capacity of the dielectric between a charged body and its bound charge increases the magnitude of the bound charge, and in this respect is equivalent to bringing the conductors nearer together. We saw in the experiment on the capacity of the Leyden Jar that bringing a bound charge nearer to a charged conductor had the effect of lowering the electric pressure upon the surface of the charged conductor. It follows that increasing the specific inductive capacity of the dielectric in the field of a charged conductor must lower the electric pressure upon the surface of the conductor.

We have assumed that this electric pressure is due to the Electric Elasticity of the dielectric. Since elasticity is measured by the resistance which a body offers to pressure, the electric elasticity of the dielectric is measured by the electric pressure which it exerts. If increasing the specific inductive capacity of the dielectric lowers the electric pressure upon a charged body, it must be that it decreases the electric elasticity of the dielectric.

A conductor immersed in paraffin will require about twice the electrical quantity to charge it so that it will have a given electrical pressure upon its surface that it would if it were in air. In alcohol, which has a specific inductive capacity twenty-five times as great as air, a conductor will require twenty-five times the electrical

quantity to produce a given electrical pressure that it will in air. It follows that what we have called the electric elasticity is about one half as great in paraffin and about one twenty-fifth as great in alcohol as in air. If the Luminiferous Ether is the medium by which electrical pressures are transmitted, the electric elasticity of the Ether must be different when it is associated with different kinds of matter. All known bodies have greater specific inductive capacities than the vacuum, hence the electric elasticity of the Ether is apparently diminished when it is associated with any kind of matter.

ELECTRIC DISCHARGE

Discharge of Electrification from a Pointed Conductor.

LABORATORY EXERCISE 101.—Provide an insulated conductor with a needle point and with a pith-ball electroscope attached at some distance from the point.

Will such a conductor retain its electrification when charged?

Hold a candle flame near the point while the conductor is being charged from the machine. Do you find indications that electrified particles are being repelled from the point?

Why should all the conductors in the preceding experiments have smooth surfaces?

Electrify an insulated conductor and hold near it an uninsulated conductor provided with a point. Does the bound charge send off electrified particles to the charged conductor?

How would such particles affect the electrification of the charged conductor?

The Spark Discharge.—We have seen that when the electric pressure between the knobs of the electric machine becomes great enough a spark will pass between the knobs, and the opposite electrifications of the two knobs will disappear. Just what takes place at the time of the discharge to cause the spark and the

equalization of the electric condition of the conductors is not known. We can learn of the conditions produced in the dielectric and the conductors by the discharge, but we do not know what is discharged.* We know that it requires the expenditure of energy to produce an electric field. The crank of the electric machine is more easily turned when the discharging knobs are in contact than when they are separated and an electric field is being formed between them. It requires more work to separate the flannel and sealing wax after they have become electrified than before. This work is represented by the potential energy of the field, which seems analogous to the potential energy of a displacement produced in an elastic body, such as the bending of a spring, the stretching of a rubber membrane, or something of a similar nature. The discharge of the electrification is like setting free the spring or membrane, and the potential energy of the charge is changed again into kinetic energy. If the discharge takes place through a long, thin conductor, the conductor is heated. If it takes place through the dielectric, the dielectric is heated; and by whatever process it takes place work is performed. If a card be held between the discharging knobs, it is perforated by the discharge. A piece of paper dipped in a solution of potassic iodide and starch shows that iodine is set free by the electric spark. Thus the energy of the discharge may be used in doing mechanical work, in producing a chemical change, and in generating heat.

Instantaneous Character of Spark Discharge.—The instantaneous character of the electric discharge may

* It seems extremely probable that the electrical charges transferred in the spark discharge are carried by the electrons referred to in the foot-note on page 165.

be shown by illuminating with the spark a rapidly moving object, as a rotating wheel. The short duration of the illumination causes the moving object to appear at rest.

Oscillatory Character of Spark Discharge.—If the image of the electric spark be observed in a very rapidly rotating mirror, it will be seen to consist of several successive sparks. The greater the capacity of the discharging conductor, the farther apart will these sparks appear. The images of these successive sparks have been projected and photographed by means of a rapidly rotating concave mirror. They are explained by supposing a discharge to take place back and forth between the discharging knobs.

Fall of Potential in Electric Conduction.

LABORATORY EXERCISE 102.—Suspend a smooth wooden rod two or three meters long by silk threads, and provide it with several pith-ball or paper electroscopes distributed at equal distances along the rod. Connect one end of the rod by a wire to a gas or water pipe, and connect the other end to one discharging knob of the electric machine, and electrify the rod as highly as possible.

Does electrification pass through the wood? Is the rod equally electrified throughout its entire length? If not, where is the electrical pressure upon the surface of the rod greatest? Where is the electric potential in the air near the rod greatest?

Connect the same knob of the machine to the same place on the steam or water pipe by a copper wire. Which carries off the charge from the machine the quicker, the rod or the wire?

Which seems to offer the greater resistance to the passage of the electric charge?

Remove the wire from the knob of the electric machine, disconnect the rod from the earth and connect its ends to the two knobs of the machine as in Fig. 77, and again electrify it as highly as possible. Where are the pith balls now

most strongly electrified? Can you find a place on the rod where a pith ball shows no electrification? Is such a place at the same electric potential as the earth? Connect such a place to the earth through the steam or water pipe. Is the difference of electric potential of the two ends of the rod apparently greater or less than between either end and the earth? If the earth be taken as at zero potential, give

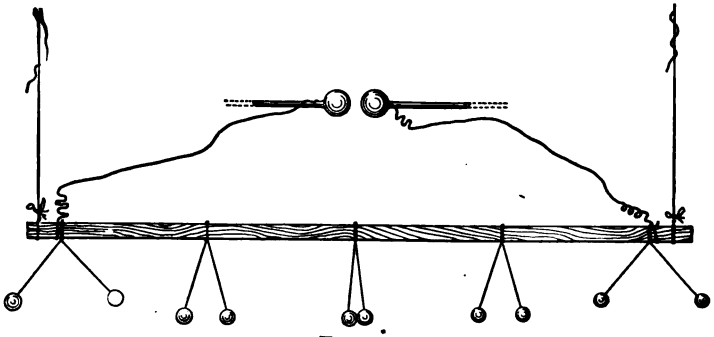


FIG. 77.

reasons for saying that one end of the rod is at a positive potential and the other at a negative potential.

If there is only one kind of electrification, give reasons for saying that a body may be more or less highly charged than the earth.

ELECTRIFICATION OF THE EARTH

The Earth's Electric Field.—We have seen reasons in the preceding experiment for believing that the earth itself is highly electrified, so that of the two electrical conditions, the positive and the negative, the one represents a higher degree of electrification than the earth, and the other a lower. Since no limit has been found to the possible intensity of either positive or negative electrification, no such thing as a total absence of electrification is known, and the absolute intensity of the earth's electrification cannot be measured.

Electrification of the Air.—The first observations on the electrification of the air above the earth were made by Benjamin Franklin in his celebrated kite experiment. Franklin was familiar with the method of discharging insulated conductors by holding a pointed conductor near them, and he conceived the idea of "drawing off" the electrification of a thunder cloud in the same way. By means of a kite provided with metallic points and attached to a moistened string held by a silk ribbon at the end, he was able to take sparks from a key suspended at the end of the string. Franklin thought of this as drawing off the electricity of the cloud. We think of it as charging the key by induction, the "bound charge" in this case escaping from the points on the kite.

Since Franklin's time many methods of finding the electric pressure at a point in the atmosphere have been tried. In one of the methods devised by Lord Kelvin an insulated vessel of water is raised to the desired height and is connected by a wire to an electroscope which is at the electrical pressure of the earth. Water is then allowed to fall in drops from the insulated vessel. Since the vessel of water is charged to the electric pressure of the earth while the dielectric in its vicinity is charged to a lower pressure, each drop of water will carry off some of the charge of the vessel and the electroscope until these are at the same electric pressure as the point from which the drops fall. By testing the electrification of the electroscope the desired electrical condition of this point may be known.

While the electrification at the same point in the atmosphere varies greatly from day to day, and while the change in electric pressure for a given elevation is

very different over different points of the earth, in general a point taken anywhere above the earth is positively electrified with reference to the earth.

Electrification of Clouds.—The small dust particles which form the nuclei of rain drops (see page 165) have floated about in the atmosphere until they have generally taken an electrical condition different from that of the earth. When condensation takes place upon them, the water drops thus formed take the electrical condition of the dust particles. As they settle into a region of different electrical pressure they are charged with reference to the surrounding dielectric. When two of them combine, the resulting drop takes the charge of both its constituent drops. The new sphere of water thus formed has accordingly twice the electric charge of either constituent sphere (assuming these to be equally charged), but has not twice the capacity of either of them. The electric capacity of a sphere increases in proportion to its radius. The radius of a sphere is not doubled when its volume is doubled. Hence the electric pressure at the surface of the new drop is greater than at the surface of its constituent drops. By the combination of many small rain drops into larger ones, the electric pressure upon the drops may become very great. This, together with the fact that the drops are constantly settling into a region of different electric pressure, may account for the very high pressures sometimes observed in thunder clouds.*

* It is also known that the negative electrons (see p. 165) which are formed by the breaking up of the gas atom are especially adapted to forming nuclei for the condensation of water drops. Drops formed about such nuclei are negatively charged, and when two such drops combine the resultant charge is the sum of the two original charges. Its electric pressure is accordingly increased in the manner mentioned

When these highly charged clouds approach the earth they induce bound charges upon the parts of the earth nearest to them. This changes the distribution of the electric field about the cloud, and when the pressure becomes great enough a disruptive discharge takes place between the cloud and the earth, or between two clouds whose nearest points are in opposite electrical conditions. This discharge, which we call Lightning, often takes place through great thicknesses of air, but generally from one conducting particle to another, and not in a straight line.

Protection from Lightning.—Franklin was the first to suggest the use of long, pointed conductors connected to earth and projecting above buildings to "draw off" the charge from adjacent clouds and prevent a disruptive discharge to the building. As we now know, the purpose served by the lightning rod is to prevent the formation of a bound charge on the building. Formerly, lightning rods were carefully insulated from buildings, but we now understand that they are more effective if in metallic contact with the conducting parts of the building.

Since the purpose of the point is to facilitate the escape of the bound charge, it should be kept sharp, and should be made of some metal not easily corroded by the action of the atmosphere.

From what we have seen of the impossibility of an electric field within a hollow conductor, it follows that the most efficient protection from lightning would be a

above. Such drops form negatively electrified clouds, and when they fall to the earth they leave the upper air, which still contains the electropositive parts of the atoms positively electrified. It is believed by many physicists that these electrons play a very important part in the electrification of the air.

conducting covering, such as a netting of wire, joined to the earth.

CURRENT ELECTRICITY

THE VOLTAIC CELL

Displacement of One Metal by Another in an Acid Solution.

LABORATORY EXERCISE 103.—Prepare a solution of copper sulphate in water in a tumbler or beaker, and place a bright piece of iron or steel in it for a few minutes. What evidence have you that the copper sulphate has been decomposed?

Repeat, using a strip of zinc, instead of iron. Is copper separated from the solution? Does zinc go into the solution?

Put two strips of zinc and one strip of copper in a vessel of the solution, putting one strip of the zinc in contact with the copper strip, and leaving the other zinc strip separated from both the other metal strips. Upon which zinc strip is the copper deposited the more rapidly? Does the other zinc strip go into solution?

Pour a little sulphuric acid into a vessel of water and dip strips of copper and amalgamated * zinc into it separately. If the metal goes into solution it drives out hydrogen gas, which can be seen as bubbles upon the surface of the metal.

Which metal seems to go into solution the more readily? Try a strip of the zinc which has not been amalgamated.

Put the copper and amalgamated zinc into the solution together, making a metallic contact between them by touching them together or by connecting them by means of a copper wire. What difference do you observe in the action of the acid upon the two metals?

Formation of Ions in the Solution.—When a metal dissolves in an acid, the molecules or parts of molecules

* The zinc is amalgamated by first cleaning it and then dipping it into a vessel containing a little mercury and some dilute sulphuric acid and while the zinc is in the liquid rubbing the mercury over it by means of a brush or a rag tied on a stick. When the zinc shows a bright coating of mercury it should be washed in water and is then ready for use.

which go into the solution are called Ions. These ions always drive out other ions of the solution. The ions which are driven out of ordinary acids by the solution of metals are hydrogen. In the copper sulphate solution copper ions were driven out by the iron or zinc.

Positive Charges of Metallic Ions.—It has been found by the use of very sensitive electroscopes that when metallic ions are dissolved off a metal plate in an acid solution they carry with them positive electric charges, and leave the metal plate negatively electrified.

Differences in Electrical Conditions of Different Metals in the Same Solution.—If two metal plates, one of which dissolves in the acid while the other does not (as zinc and platinum) be put into an acid solution, the plate which dissolves becomes electro-negative to the other. If both plates dissolve in the acid, the plate which dissolves the more rapidly becomes electro-negative to the other.

Production of the Electric Current.—If the plates be connected by a conductor they necessarily acquire the same potential, and the ions which are driven out of the solution go to the plate which dissolves least. Since the ions take away positive charges from one plate and carry positive charges to the other, they tend to cause a difference in the electrical potential of the two plates, and this difference can be neutralized only by the passage of positive electricity along the conductor joining the two plates.

Thus with plates of zinc and copper in copper sulphate solution, the zinc ions replace the copper ions in the solution, and the copper ions are deposited upon the copper plate. The zinc plate is continually becom-

ing more electro-negative and the copper plate more electro-positive, and this condition is neutralized by the electrical flow, called the current, along the wire from the copper to the zinc.

If the plates be disconnected, the copper plate soon becomes so strongly electro-positive that it repels the positively charged ions in the solution, and these in return repel the positive ions which are leaving the zinc plate and prevent their escape into the solution. Accordingly, in this condition the solution of the zinc plate may cease entirely.* The plates are then said to be polarized.

Construction of the Voltaic Cell.—The arrangement of the zinc and copper plates with a dissolving liquid to give an electric current is called a Voltaic Cell. Many other metals and liquids may be used in the voltaic cell. The zinc and copper combination is frequently used, as is also the combination of zinc and carbon with a liquid which gives off hydrogen ions when the zinc dissolves in it. The hydrogen is absorbed by the carbon until the carbon becomes saturated with it, after which it rises in bubbles to the surface. Since the difference of potential between zinc and hydrogen cannot become as great as between zinc and carbon, an oxidizing substance of some kind is frequently combined with the carbon, or the carbon is placed in a porous cup containing a strong oxidizing

* This is true only when the zinc is pure. If it contain iron or other metals, the action may go on between different points on the surface of the plate, ions being given off by the zinc and other ions being deposited upon the iron or other metal. To prevent this action, the zincs used for generating a current are usually amalgamated. The mercury dissolves the zinc and brings zinc ions to the surface continuously, while it does not dissolve the impurities which are electro-positive to the zinc.

agent, as nitric or chromic acid, to keep the carbon surface free from hydrogen.

PROPERTIES OF THE ELECTRIC CURRENT

Magnetic Field of the Current.

LABORATORY EXERCISE 104.—In the following exercise a voltaic cell giving a stronger current than the zinc and copper strips of the previous experiment should be used. An Edison-Lalande cell, in which zinc and copper oxide plates are placed in a strong solution of caustic potash, is well adapted to our purpose.

Connect the plates of the Edison-Lalande cell by a piece of rather coarse, bare copper wire about two feet long, and dip the middle of the wire into iron filings. What evidence have you of magnetic action?

N.B. Always disconnect the wire from one terminal of the cell when not in use. Why?

Lay a piece of cardboard on some convenient support, make a small hole through it, and pass the copper wire from the cell through the hole, keeping the wire vertical. Connect the wire with the terminals of the cell and scatter iron filings on the cardboard around the wire. Tap the cardboard until the filings arrange themselves in lines. Do the lines of the magnetic field radiate from the wire, or do they circle around it?

Direction of the Lines of Magnetic Force about a Current.

By the aid of a small, suspended magnetic needle, determine the positive direction of the lines of magnetic force in the field about the current. Assuming that the current is flowing along the wire from the copper or carbon plate to the zinc plate, look along the wire in the direction of the current and tell whether the magnetic lines of force are in the same direction or the opposite direction to the motion of the hands of a watch.

Take hold of the wire with your right hand with your thumb pointing in the direction of the current. Do your fingers point in the direction of the lines of magnetic force or in the opposite direction?

Bend the wire into a loop without allowing it to touch

where it crosses, and place the magnetic needle inside the loop. Looking in the positive direction along the lines of magnetic force, is the direction of the current around the needle clockwise or counter-clockwise?

Take hold of the needle with one hand so that your thumb will point in the positive direction of the lines of magnetic force and your fingers in the direction of the current. Which hand must you use?

Give a rule for determining the direction of a current along a wire by means of a magnetic needle.

Give a rule for finding the north-seeking pole of a magnet by means of a wire carrying a current.

Temperature Effect of Current.

LABORATORY EXERCISE 105.—Connect the terminals (called the poles) of your Edison-Lalande cell by a short piece of fine iron or German silver wire. What temperature change takes place in the wire?

Chemical Effect of Current.

LABORATORY EXERCISE 106.—Dip a piece of filter paper or blotting paper into a solution of starch to which some of a solution of potassic iodide has been added. (A blue color in the starch is a sign of free iodine, and a solution which is colored blue should not be used.) Connect two short copper wires to the poles of your cell and bring their ends near together and in contact with the moist paper. Is there an indication of chemical action?

Connect the poles of the electric machine by a strip of the same moist paper while you excite the machine.

What changes may accompany the passage of an electric current along a wire or through a solution of potassic iodide?

Each of these properties of the current will be studied more thoroughly under special heads.

MAGNETIC EFFECTS OF THE CURRENT

Rotation of a Magnetic Pole about a Current.

LABORATORY EXERCISE 107.—We have seen that a current along a straight wire apparently has a circular magnetic field about it. This being true, a free magnetic pole should move in a circle about a straight current. This deduction may be tested by the following experiment:

Magnetize strongly a knitting-needle and suspend it by a fine thread tied around its south-seeking end to a convenient support two or three feet high. The needle will then hang vertical with its north-seeking pole downward.

Place an upright brass or copper rod, as the rod of a ring stand, or a large copper wire held upright by means of a

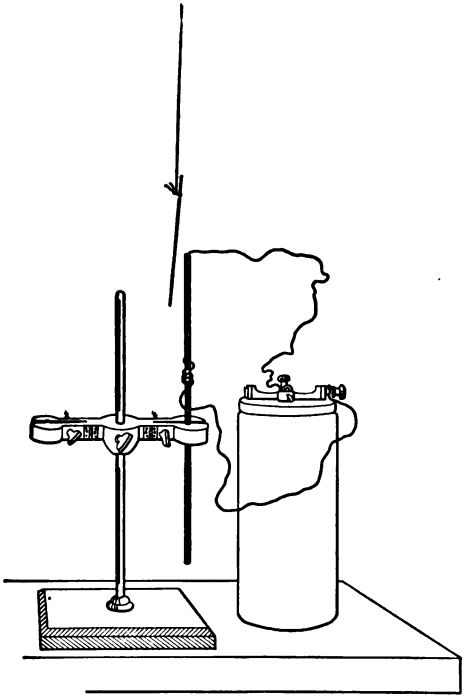


FIG. 78.

convenient clamp, directly below the point of attachment of the thread to its support and so that its top will reach nearly to the center of the suspended needle. The needle will then rest against the rod. Attach one wire of the Edison-Lalande cell (or some other low-resistance cell) to the lower end of the brass or copper rod, and taking the wire from the other

pole of the battery in the hand, and holding the wire horizontal, touch its end to the top of the rod, as shown in Fig. 78. As soon as the current is set up in the rod, the needle will start to rotate around it. Take the wire away from in front of the needle and make the contact again immediately behind the needle as soon as it has passed. By removing the wire for the needle to pass, and keeping it upon the rod the rest of the time, the needle can be made to swing with accelerated velocity around the current.

Change the direction of the current by connecting the other pole of the cell to the bottom of the rod and note the direction of the rotation of the magnetic pole around the wire. Looking along the rod in the direction of the current, is the rotation of the magnetic pole clockwise or counterclockwise about the current?

With which hand must you take hold of the rod with the thumb pointing in the direction of the current so that the fingers may point in the positive direction of the lines of magnetic force?

The Galvanometer.—The galvanometer is an instrument for the detection and measurement of an electric current by means of its magnetic properties. Galvanometers are of two general types. In one a magnetic needle is suspended inside a coil of a number of windings of insulated wire. When a current passes along the wire, the magnetic field set up around each loop acts upon the needle to cause it to set in a definite direction. If this direction is not the same as the direction which the needle takes in the earth's field, then the direction of the needle will indicate the direction of the current in the wire.

In the other type of the galvanometer a coil of insulated wire is suspended in a strong magnetic field, as between the poles of a strong horseshoe magnet. When a current is sent through the coil of wire, it will tend to rotate into a position in which its lines of mag-

netic force are in the same direction as those in the field of the magnet.

A small compass set in a hole in a block of wood with an insulated wire wound around it several times in the N.S. direction will serve very satisfactorily for the detection of currents.

The Solenoid.—We have already seen that a circular current has its included magnetic lines of force perpendicular to the plane of the circle, and that this fact is made use of in the construction of the galvanometer. A coil of wire so wound that a current may pass continuously around it from one end to the other is called a Helix or Solenoid.

How should the magnetic lines of force run about a solenoid carrying a current?

Magnetic Field of a Solenoid.

LABORATORY EXERCISE 108.—Attach the terminals of a voltaic cell to the ends of a solenoid which has been wound on a tube of cardboard or some other non-magnetic material, and by means of a small compass or other magnetic needle map the lines of magnetic force in and about the solenoid.

In what respects is the solenoid analogous to a bar magnet?

In what respect does it differ from a bar magnet?

At which pole of the solenoid must you look in order that the current may go around it clockwise?

The Electro-magnet.—We have seen in former experiments that iron has a much greater magnetic permeability than air, and that a piece of iron placed in a magnetic field has more magnetic lines of force passing through it than formerly existed in the same part of the field.

Where would you place an iron bar to have as many as possible of the magnetic lines of force of the solenoid pass lengthwise through it?

Magnetization by Means of a Solenoid.

LABORATORY EXERCISE 109.—Place a bar of iron in such a position with reference to a solenoid as to make the largest possible number of lines of magnetic force pass through it. Does it increase the strength of the magnetic field of the solenoid?

Take a solenoid provided with a movable core of soft iron, remove the core and send a current through the solenoid. Hold the solenoid so that it will produce a slight deflection of a magnetic needle, and without moving it, push the iron core slowly into the coil. Explain the effect upon the magnetic needle.

A solenoid with its iron core is called an Electro-magnet.

What explains the difference in the strength of the magnetic field of a solenoid and its electro-magnet?

What effect should it have upon a bar of steel to thrust it into a solenoid through which a current is passing?

Perform the experiment with an unmagnetized knitting-needle, and explain the effect upon it.

Can you reverse the magnetic polarity of a magnetized knitting-needle by means of the solenoid?

The Electro-magnetic Telegraph.—There are very many important practical applications of the electro-magnet. One of the best known of these is the electro-magnetic telegraph. This is made in several different forms. The one in most common use in this country is the Morse Sounder. In this instrument a U-shaped electro-magnet is fastened to a block and has a pivoted bar placed above it and between its poles. A piece of soft iron, called the armature, is placed across the pivoted bar so as to lie directly over the poles of the magnet. One end of the pivoted bar is held down by a spring, and the other end is free to move up and down between two stops placed at a distance apart a little greater than the width of the bar.

When there is no current through the electro-magnet, the bar is held against the upper stop by the pull

of the spring upon its other end. When a current is sent through the magnet, the bar is pulled down and strikes the lower stop, making a sharp click. When the current is broken it flies up and clicks against the upper stop. By making and breaking the current by

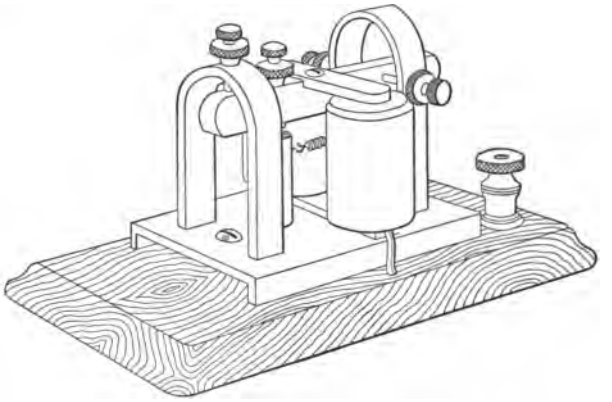


FIG. 79.

means of a suitable key, the sounder is made to click the signals of the Morse alphabet.

The Electric Bell.—Describe the construction and mode of working of an ordinary electric bell and its push button.

ELECTRO-MAGNETIC INDUCTION

Induction of Current by Moving Magnet.

LABORATORY EXERCISE 110.—In the preceding laboratory exercises we saw that an electric current induces a magnetic field in its immediate vicinity. We now wish to try the inverse process and see if a magnetic field may induce an electric current.

Connect the ends of a solenoid by means of long wires to a galvanometer. Place the solenoid at such a distance from the galvanometer that a bar magnet moved about near the

solenoid will not deflect the galvanometer needle. Take a strong bar magnet in the hand and thrust it suddenly into the solenoid. Does it induce a current in the wire of the solenoid?

Does the current continue after the magnet has come to rest?

Draw the magnet suddenly out of the solenoid and observe the galvanometer. Is a current produced? If so, how does it differ from the current produced when the magnet was thrust into the coil?

In which case is the current induced in the solenoid in the same direction as the current about an electromagnet having its poles in the position of those of the bar magnet?

Repeat the experiment, keeping the magnet at rest and moving the solenoid over it. Are the effects the same?

Can you get induced currents from the solenoid when it is at rest with reference to the magnet? (Try moving both together.)

State the law of the induction of currents in a solenoid by a moving magnet.

Induction of Current by the Magnetic Field of Another Current.

LABORATORY EXERCISE 111.—Prepare two solenoids so that one can be placed inside the other. Connect the terminals of the outer coil to a galvanometer, and the terminals of the inner coil to a voltaic cell. Try to induce currents in the outer coil by means of the magnetic field of the inner coil. Describe your method and results.

Under what conditions is the current induced in the outer coil in the same direction as the current of the inner coil?

Put a core of soft iron in your inducing coil and explain the change in its inducing effect.

Connect the outer coil to the cell and the inner to the galvanometer. Can you produce the same effect as before?

Connect the inner coil to the cell, the outer to the galvanometer, and make and break the current in the inner coil.

To what movement of the coil is the setting up of the current equivalent? The breaking of the current?

Calling the induced current direct when it is in the same direction around the coil as the inducing current, and inverse when it is in the opposite direction, tell of two ways in which

an inverse current may be induced. Two ways in which a direct current may be induced.

When magnetic lines of force are passed through a closed wire circuit, what takes place in the circuit?

When the number of lines of magnetic force through a circuit is increased, is the current induced in the circuit a direct or an inverse current?

Primary and Secondary Currents.—In the experiments in which a current flowing through one solenoid is made to induce a current in another solenoid, the coil through which the inducing current flows is called the Primary Coil, and the coil in which the current is induced is called the Secondary Coil. The inducing current is sometimes called the Primary Current, and the induced current the Secondary Current.

Potential Difference Induced at Terminals of Secondary Coil.—We know that the current which has been made to flow through the galvanometer in these experiments indicates that the two ends of the secondary coil which are connected to the galvanometer are at different electric potentials, and that this potential difference has been produced in some way by the magnetic field of the primary current. It has been found that the potential difference induced in the two ends of a secondary coil by a given primary current is proportional to the number of turns of wire in the secondary coil. If the secondary have the same number of turns as the primary, and if it be placed so that the entire magnetic field of the primary will pass through it, the potential difference induced in the secondary if the primary be suddenly broken will be the same as that of the primary, which is due to the plates of the cell to which it is attached. If the secondary have ten times the number of windings of the primary, the potential

difference induced at its ends may be ten times the potential difference at the terminals of the primary. If, on the other hand, the primary have ten times the number of coils of the secondary, the potential difference induced at the ends of the secondary will be only one tenth that at the terminals of the primary. This fact makes it possible to change an instantaneous current of low potential difference into one of high potential difference, and *vice versa*.

The Induction Coil.—The induction coil is an instrument for changing an interrupted current of low potential difference into one of high potential difference. It consists of two solenoids, generally placed with the secondary outside the primary. The secondary generally consists of a large number of turns of wire, and in order that it may not be too large and too heavy, fine wire is generally used. The terminals of the secondary are generally connected to binding posts, and the primary generally has a core of soft iron to strengthen its magnetic field, and an automatic device for breaking and closing its circuit with the voltaic cell.*

Experiments with Induction Coil.

LABORATORY EXERCISE 112.—Connect a small induction coil to a voltaic cell. Describe by means of a diagram the automatic interrupter of the coil. When the primary current is being rapidly made and broken, attach a wire to one terminal of the secondary and see whether you can get a spark to pass from it to the other terminal without bringing them in contact.

*When not provided with an automatic interrupter, one terminal of the coil may be connected directly to the cell and the other terminal to a coarse file. The wire from the other terminal of the cell may then be taken in the hand and its end drawn along the file, making and breaking the circuit through the file.

Moisten the fingers and touch both terminals of the primary. Of the secondary.

What other evidence do you find that the potential difference between the terminals of the secondary is greater than that between the terminals of the primary?

The Dynamo Machine.—Most of the electrical currents used for technical purposes are now derived from electro-magnetic induction by means of machines called Dynamo Machines. The construction of these machines may be understood from the accompanying diagrams.

In diagram A, Fig. 80, *c* represents a closed coil of

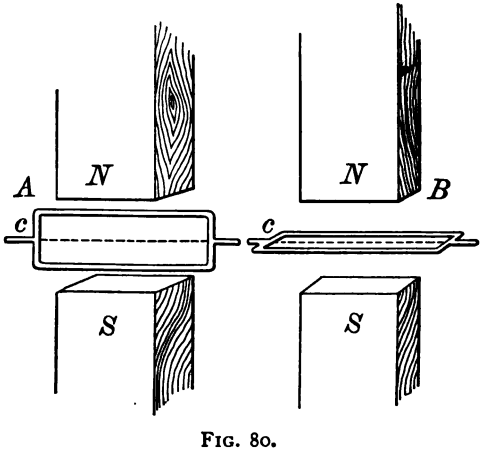


FIG. 80.

wire lying between a pair of magnetic poles and parallel to the lines of magnetic force of the magnets. If the coil be rotated into the position shown in diagram B, the number of lines of magnetic force passing through the coil will be greatly increased. While this increase is taking place, a current will flow around *c*. If the coil continues to rotate until it is again parallel to the magnetic lines of force, the number of these lines pass-

ing through it will decrease again to zero, and while this decrease is taking place a current will be induced around the coil in the opposite direction to the first one. If the coil be continuously rotated in the magnetic field, a current will be induced in it alternately in one direction and in the other. Such a current is called an Alternating Current, and such a machine is called an Alternating Current Dynamo.

By increasing the number of rotating coils the intensity of the current may be correspondingly increased. These rotating coils are insulated from each other, and are wound in many different ways in different machines. The magnet used in dynamo machines is an electromagnet, and in some machines the entire current generated is sent around the magnet, while in others the magnet is separately excited, that is, is magnetized by a current from another dynamo.

One important consideration in designing a dynamo is to confine the magnetic field as much as possible to the region in which the coil (called the Armature Coil) rotates. To accomplish this, the magnets are so shaped as to make the air spaces between them and the armature coil as small as possible.

The Direct-current Dynamo.—If it is desired to have the current from the dynamo always in the same direction after leaving the armature, some form of device known as a commutator must be used. One of the simplest forms of commutator is shown in diagram in Fig. 81. A split tube of copper connected with the terminals of the coil is placed on an insulating cylinder which rotates with the coil. Two strips of copper or carbon, known as brushes, rest against the copper and serve to carry off the current. In the figure the upper

part of the coil is represented as rotating toward the observer, and the current flows in the direction indicated by the arrows. When the coil has rotated through 90 degrees the direction of the current through the coil will change, but at the same time the brushes which carry off the current will change to the other halves of the commutator ring, and the current will

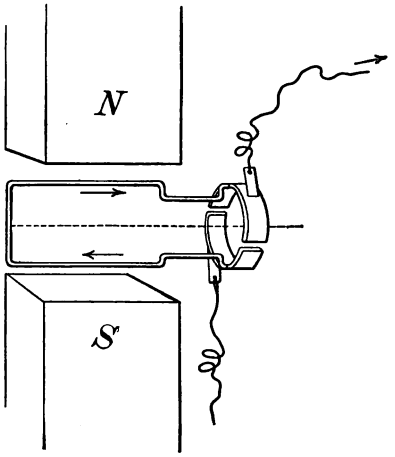


FIG. 81.

continue to pass out through the brushes in the same direction as before.

Dynamo machines driven by steam engines or water power now furnish most of the electrical currents used for practical work. In all dynamo currents, the energy of the electric current is derived from the mechanical energy used to run the generator.

Electric Motors.—If an electric current be run through the armature of a direct current dynamo, the

armature will revolve. Thus in the coil shown in Fig. 81, if a current be allowed to enter through one of the brushes and pass out through the other, the armature coil will rotate until its lines of magnetic force are parallel to those of the magnet. Just as it reaches this position, the brushes change to the opposite sides of the commutator ring, and the direction of the current through the coil is reversed. This reverses its magnetic field, and causes it to rotate until its field is again brought into parallelism with that of the magnet, at which instant it is again reversed.

If an alternating-current dynamo be run as a motor, it must be driven by an alternating current which will reverse its direction through the armature at the proper time without the aid of a commutator.

Most of the modern alternating-current motors are known as polyphase motors, and are run by a current which is divided into two or more currents which run through different coils of the armature, and which reverse their direction at different times, so that they are not all in the same phase. The principle upon which these polyphase motors work has not been discussed in these lessons.

The dynamo and motor combined serve as a means of distributing power more easily and economically than by any other method. In other ordinary methods of power distribution the engine must be coupled to the machine which it runs by means of a shaft, belt, or cable, so that the distance between the machine and engine cannot be great. In the electrical distribution of power, the engine and dynamo are coupled together, and the current may be carried over wires to a great distance to the motor which drives the machine.

Experiments with the Dynamo Machine and the Motor.

LABORATORY EXERCISE 113.—Examine and describe the parts of a small motor. (A toy motor costing one or two dollars is sufficient.)

Attach it to a cell and run it as a motor, then disconnect from the cell and attach it to a galvanometer and run it as a dynamo.

To get a current in the same direction through the armature as the current of the cell, do you rotate the armature in the same direction that it was rotated by the cell, or in the opposite direction?

The Transformer.—In the distribution of power by means of alternating dynamo currents it is often economical to use what are known as high potential currents, that is, currents in which the potential difference between the two wires from the dynamo is very great. Such currents are not well adapted to running motors or lighting houses, and accordingly some method of reducing the potential difference is needed. The instrument by which this is accomplished is called

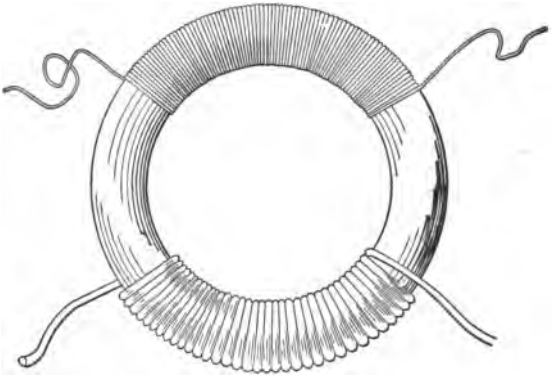


FIG. 82.

a Transformer. In principle, it is a reversed induction coil. One of its simplest forms is an iron ring upon which are wound two coils of insulated wire, the one made of many turns, and the other of only a few as shown in Fig. 82. The alternating current is run through the longer coil, and at each reversal it induces currents of lower potential difference in the shorter coil. These currents are then led to the motor or the electric lamp.

The Electro-magnetic Telephone.

LABORATORY EXERCISE 114.—Another important instrument based upon the principles of electromagnetic induction is the Telephone. One form of the telephone may be understood from the following exercise:

Connect the terminals of a solenoid to a galvanometer, place a bar of soft iron in the solenoid, and bring one pole of a magnet suddenly near the end of the bar. Explain the effect upon the galvanometer.

Remove the bar of soft iron and insert a bar magnet into the solenoid. After the galvanometer has come to rest, bring the bar of soft iron suddenly near one pole of the magnet. If your galvanometer is sufficiently sensitive, it will show that you have induced a current in the solenoid. Explain this current.

Induction of Telephone Current.—The so-called Telephone Current is induced as follows: A bar mag-

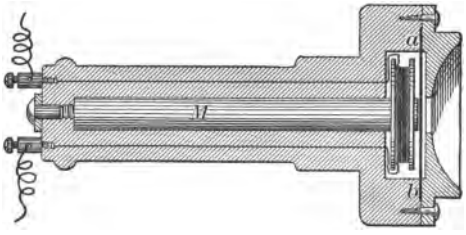


FIG. 83.

net, *M* in Fig. 83, has a coil of insulated wire wound around one pole, and a thin disc of iron, *ab* in the

figure, fixed parallel to and very near the same end of the magnet. A mouthpiece is fitted just outside the iron disc. When words are spoken into this mouthpiece, the sound waves of the voice set up vibrations in the iron disc and cause it to alternately approach and recede from the end of the magnet. The vibrations of the disc change the strength of the magnetic field, and accordingly the number of magnetic lines of force which pass through the coil, and thus induce momentary currents in opposite directions through the coil.

Production of Sound Waves by Telephone.—If an exactly similar instrument be placed at a distance and the coils of the two instruments be connected, the currents induced in one coil will flow through the other and alternately strengthen and weaken the field of its magnet. This will cause the attraction between the magnet and its iron disc to vary, and will set up vibrations in the disc corresponding to the vibrations set up by the voice in the other disc. These vibrations of the disc will, in turn, set up sound waves in the air corresponding more or less closely to the sound waves of the voice at the other end of the line.

The Bell Telephone.—This is the telephone invented in 1876 by Graham Bell, and known as the Bell Telephone. The instrument used by the speaker is called the transmitter, and the one used by the hearer is called the receiver. The same instrument is alternately used as a transmitter and as a receiver.

Other Forms of Telephone.—In the more recent telephones an instrument of the Bell pattern is used as a receiver, and an entirely different instrument, based upon the change of the electrical conductivity of carbon

for a change of pressure, is used as a transmitter. In this instrument the telephone current is not an induced current, but is furnished by a voltaic cell. This current passes from the vibrating plate of the mouthpiece through a disc or ball of carbon and through the coil around the magnet of the receiving telephone. The vibrations of the transmitter disc cause a variation of the pressure between it and the carbon. When this pressure is increased more current flows, and when it is diminished the current is weakened. These variations in current strength cause the changes in the magnetic field of the receiver to which the vibrations of its disc are due.

HEATING EFFECT OF CURRENT

Work Done in Overcoming Resistance of a Conductor.—We have seen in the experiments on static electricity that some substances offer a greater resistance to the passage of an electric charge than others, and we saw in Laboratory Exercise 105 that a wire may be heated by the passage of an electric current through it. This heating effect is due to the resistance of the wire. If an electric charge or an electric current is driven through a conductor against a resistance, work must be done, since work is done whenever resistance is overcome through space.

Energy Used in Heating Conductor.—The nature of electrical resistance is not known, since it is not known what actually passes along a conductor carrying a current. It is a well-known fact, however, that some substances require a much greater expenditure of energy to force a current through them than do others, and this energy is employed in heating the conductor.

Thus all the work done in forcing a current through a wire is changed into heat in the wire.

Resistance of Uniform Conductor Proportional to its Length.—If a current be driven through a conductor of uniform resistance, the conductor will be uniformly heated throughout its length. If some parts of the conductor offer greater resistance to the passage of the current than other parts, these parts are most heated. Since a uniform conductor is heated alike throughout its entire length by the passage of a current, it follows that the amount of energy required to drive the current through the conductor is proportional to its length. Hence the resistance of a uniform conductor is proportional to its length.

ELECTRICAL UNITS AND MEASUREMENTS

Practical Units.*—Since electrical currents have come to be so commonly used for transmitting power, practical units of Electromotive Force, Current, and Resistance are needed. These practical units are not based directly upon the absolute units used in electrostatics, but their relations to the electrostatic units are known.

The Volt.—The practical unit of electromotive force now in general use throughout the world is called the Volt. It is very approximately equal to the electromotive force of the ordinary Daniell's cell, or gravity cell, in which one metal is zinc in dilute sulphuric acid or a solution of zinc sulphate, and the other copper in a solution of copper sulphate.

The electromotive force of the Edison-Lalande cell is approximately .8 volt.

* For technical definition of units see appendix A.

The Ohm.—The practical unit of resistance is the Ohm. It is very approximately the resistance of a column of mercury one square millimeter in cross-section and 106 centimeters long at the temperature of melting ice, and is very nearly the resistance of a No. 20 copper wire 96 feet long.

The Ampere.—The Ampere is the unit of current intensity. It is the current which is produced by an electromotive force of one volt in a conductor having a constant resistance of one ohm.

The Joule.—The energy expended in driving a current of one ampere through a resistance of one ohm for a period of one second is called a Joule. It is equivalent to 10,000,000 ergs, or to .236 gram-calorie. Thus a current of one ampere through a resistance of one ohm would generate one gram-calorie of heat in 4.24 seconds.

The Watt.—The power (see page 11) unit corresponding to the joule is the Watt. Thus an electrical generator has a working capacity of one watt when it does work at the rate of one joule per second, i.e., when it sets up a current of one ampere through a resistance of one ohm.

The Kilowatt.—The Kilowatt is 1000 watts. The capacity of dynamo machines is generally expressed in kilowatts as the working capacity of steam engines is expressed in horse-powers. The horse-power is equivalent to 746 watts, nearly, hence to .746 kilowatt.

Ohm's Law.—It has been found that to drive the same current (measured by the same deflection of a magnetic needle) through different conductors the electromotive force (see page 268) must be increased just in proportion as the resistance of the conductor is

increased. Thus the current is diminished as the resistance is increased, or is increased as the electromotive force is increased. Expressed in the form of an equation, Current Strength $= \frac{\text{Electromotive Force}}{\text{Resistance}}$, or $C = \frac{\text{E.M.F.}}{R}$. This law was first stated by Dr. George Ohm in 1827, and has since been known as Ohm's Law. Stated in terms of electrial units, Ohm's Law becomes amperes $= \frac{\text{volts}}{\text{ohms}}$.

Joule's Law.—Instead of measuring the current strength by the deflection of a magnetic needle, it may be measured by the quantity of electricity which passes any given cross-section of the conductor in a unit of time as determined by any other method. The quantity of electricity displaced in one second by a current of one ampere is called a Coulomb. Thus the current in amperes is equal to the total electrical quantity displaced measured in coulombs, divided by the time of flow expressed in seconds, or $C = \frac{Q}{t}$.

From the discussion on page 267 we know that the work done in moving an electric quantity Q in an electrical field is $W = Q(V - V')$. If this amount of work is done in time t, then the rate of work, that is, the power of the current, is $P = \frac{Q(V - V')}{t}$. But since $\frac{Q}{t} = C$, the power of an electric current is

$$P = C(V - V').$$

When C is expressed in amperes and $(V - V')$ in volts, the power is expressed in watts, hence the work-

ing capacity of an electric generator of any kind may be found by multiplying the number of amperes it is capable of giving by the number of volts potential difference it is capable of maintaining at its terminals in the meantime.

In a given conductor, doubling the potential difference at its terminals will also double the strength of the current flowing through it; hence it will increase the *power* of the current fourfold. Since energy is supplied to the conductor four times as fast as before, and since this energy is all transformed into heat in the conductor, the heating effect of the current will be increased fourfold by doubling the current. Hence the energy transformed into heat in a given conductor carrying a current is proportional to the square of the current.

This fact was discovered experimentally by Dr. J. P. Joule and was announced by him in 1841, and it has since been known as Joule's Law.

Since the heat generated in a uniform conductor is proportional to the length of the conductor, it is proportional to the resistance; hence we may write $E = C^2Rt$, where E represents the energy measured in joules which is transformed into heat by a current through a conductor. Expressed in terms of heat calories, the equation becomes $H = \frac{C^2Rt}{4.24}$.

PROBLEMS.—A current of 3 amperes is maintained through a resistance of 5 ohms. What is the potential difference at the terminals of the resistance?

What is the working capacity in watts of the battery which supplies the current?

How many such batteries would be required to furnish a horse-power?

How many gram-calories of heat are generated in the resistance in one minute?

A coil of wire having a resistance of 5 ohms is placed in a calorimeter containing 500 grams of water at a temperature of 10° C. A current of 2 amperes is run through the coil for ten minutes; neglecting the heat capacity of the wire and the calorimeter, what is the temperature of the water?

An incandescent lamp having a resistance of 200 ohms and carrying a current of ½ ampere is immersed for ten minutes in 1000 grams of alcohol and produces a temperature change of 12°. What is the specific heat of alcohol?

PRACTICAL APPLICATIONS OF ENERGY OF THE CURRENT

Electric Lighting.—The heating effect of the current is made of great practical use in electric lighting. This is accomplished by concentrating most of the resistance of the circuit in certain conductors which are heated to incandescence by the current.

The Incandescent Lamp.—There are two general forms of electric lights, known as the incandescent, or glow, lamps and the arc lamps. In most of the former a conductor of carbon having a very high resistance is enclosed in a glass bulb from which the air has been exhausted, so that the carbon cannot burn, and is heated white hot by a current which enters and leaves through small platinum wires sealed into the glass. The carbon filament is made from a small strip of bamboo fiber or from a silk or cotton thread which has been carbonized by heating it red hot in an atmosphere of gasoline vapor or some hydrocarbon vapor in which it cannot take fire.

The carbons of incandescent lamps are adjusted to a definite resistance so that they will be heated to the proper temperature by a certain potential difference (usually from 50 to 150 volts) maintained at their

terminals. They are then connected between two wires which are maintained at this potential difference.

A 16-candle-power lamp has when hot a resistance of 200 ohms and is used on a circuit having a potential difference of 100 volts. What is the cost of running the lamp at the rate of ten cents per kilowatt-hour?

The Arc Lamp.—The arc light is produced by the passage of a current between two carbon points, usually in the air. The current is first started with the carbons in contact, after which they are separated by hand, or by a magnetic device worked by the current. When they are separated, a very high resistance is developed in the air gap between them, and the ends of the carbons and the intervening air are made very hot. The hot air becomes a conductor, and the current continues to flow. The heat generated at the surface of the carbon is sufficient to vaporize some of the carbon, and the air space between the carbon points becomes filled with incandescent carbon vapor. This and the hot ends of the carbons are the principal source of light in the electric, or voltaic, arc.

Efficiency of Lamps.—The ordinary arc lamp gives about one candle-power for each watt, while an incandescent lamp uses three or four watts per candle-power.

Electric Welding.—The great heat developed at the air space in the voltaic arc is often used to soften metals for welding. The ends of two metal bars are brought together and the heat developed by the high resistance at their junction is sufficient to melt the ends of the bars. They are then forced together under heavy pressure, and the current is turned off. Iron or steel bars as large as railroad rails are often welded in this way.

The Electric Furnace.—The electric furnace is a device for utilizing the high temperature of the electric arc, which may be as great as 8000° C., for melting refractory substances and for producing chemical changes which take place only at high temperatures. Many forms of the electric furnace are in use, some of them being adapted to metallurgical operations on a large scale, as the reduction of aluminum from its ores.

A simple form of the electric furnace is made by forming a cavity in a block of lime or fire-clay, and introducing the carbons through holes in the block. The substance to be heated is placed between and just below the ends of the carbons which are directed downward at an angle with each other.

Electric Heating.—It is plain that the electric current may be used for heating and cooking purposes, but its expense precludes its use in this way except in rare cases.

If electric power costs at the rate of ten cents per kilowatt-hour, what will be the cost of heating four liters of water from 20° C. to the boiling point, supposing twenty per cent of the heat to be lost to the air and the containing vessel?

Loss of Energy in Electrical Transmission.—In all electrical distribution of power a portion of the energy is used in driving the current through the distributing wires to the places where it is to be used. Since the rate at which energy is carried by the wire is $P = C(V - V')$, it is possible to increase this rate by increasing either the potential difference or the current. If the energy were all used in the line wire, increasing the potential difference would increase the current also; but if the energy is mostly used in other conductors

along the line, as electric lights, the potential difference may be greatly increased without producing a corresponding increase in the current. Thus, suppose it is desired to run 100 electric lamps of 16 candle-power on a circuit. If each lamp requires a power of 50 watts to sustain it, this may be produced in various ways. Thus it may take a current of half an ampere with a potential difference of 100 volts, or a current of one ampere with a potential difference of 50 volts. In the one case the line wires would be kept at a potential difference of 100 volts, the lamps would each have 200 ohms resistance and would be connected across the wires, and the wires would carry 50 amperes of current. In the other case the wires would be kept at a potential difference of 50 volts, the lamps would have a resistance of 50 ohms and would require 100 amperes of current.

We have seen that the loss of energy in the wires is expressed by the equation $E = C^2Rt$. If the resistance of the line wires remains the same in the two cases, the heating effect of the current in the line is four times as great in the second case as in the first. To reduce this loss of energy to that of the first case, the resistance of the line wires must be made only one fourth as great, that is, their carrying power must be made four times as great, hence four times as many wires of the same size must be used.

It is accordingly much more economical to distribute the energy at a high potential difference, especially where it is to be carried to a great distance. A potential difference of from 2000 to 6000 volts is sometimes used in arc lights for lighting streets, but such potential differences are dangerous in houses or where persons

may come in contact with the wires. In such cases a potential difference of 200 volts is as great as is regarded as safe, and 100 volts is considered safer. It is for the purpose of reducing these high potential differences to the safe lower potential differences that transformers are used. When it is thought desirable to distribute the power at a high potential difference, alternating currents are used, and these are run through long transformer coils of high resistance and induce currents of lower potential difference and greater current strength in the shorter coils of the transformers. Thus since the rate at which the energy is used in inducing the new currents is $P = C(V - V')$, if $(V - V')$ be reduced from 1000 to 100, C will be increased ten times, providing there is no loss of energy to the transformer. There is, however, always a loss of energy in the transformer, the iron core of which becomes heated.

In long-distance transmission of power by electric currents potential differences of 60,000 volts have been successfully used, and several electric plants distribute power at a potential difference of 40,000 volts.

CHEMICAL EFFECTS OF THE CURRENT

Current Through Solutions Accompanied by Chemical Changes.—We have already seen that the generation of a current in the voltaic cell is accompanied by chemical changes; that owing to a greater tendency of one metal to go into solution it discharges positively charged ions into the solution, while the electro-positive ions of the substance already in solution go to the other plate of the cell, carrying their positive charges with them.

If two conducting plates which do not go into solution be connected to the terminals of a battery of voltaic cells or a dynamo and be kept at a constant difference of potential while in a solution of a metallic salt or an acid, a current will be set up in the liquid by means of the ions of the dissolved substance, the electro-positive ions going to one plate and the electro-negative ions to the other.

Conduction of Current by Copper Sulphate Solution.

LABORATORY EXERCISE 115.—Place two rods or plates of carbon in a water solution of copper sulphate, connect them by means of copper wires to the terminals of a galvanometer, and determine whether any current is passing through them. Is there any evidence of chemical action in the liquid?

Introduce into the circuit between the carbons and the galvanometer two voltaic cells which have been joined together by a copper wire from the zinc of one cell to the copper or carbon of the other. Does a current now pass through the liquid?

After the current has been established for a short time, withdraw the carbons and examine them for indications of chemical action.

The electro-positive ion of the solution travels in the direction of the current. Which is the electro-positive ion?

Repeat the experiment, using strips of copper foil in place of the carbons. After the current has been established for some time, examine both copper strips for evidence of chemical action. What evidence have you that the electro-negative ion goes to one strip?

After one of the carbons in your first experiment has become coated with copper, how would you change the battery connection to remove the copper?

Suggest a method of electroplating a conductor with copper. With silver.

This method of plating one metal with another is extensively used in the arts.

Dissociation of Water by Current.

LABORATORY EXERCISE 116.—A glass vessel has two small rods of carbon or strips of platinum sealed into its bottom and connected to copper wires.* Fill the vessel to a height of about a centimeter above the tops of the carbons with water to which about five per cent of sulphuric acid has been added. Fill two test tubes with water and invert them in the vessel and over the carbons, raise them until their mouths are just below the tops of the carbons, and fasten them in this position.

Attach the wires to as many cells as you have at hand, joining the cells in line with the zinc of one attached to the carbon or copper of the next one, and attaching the free zinc to one wire and the free copper to the other.

Observe the bubbles of gas which come off from the carbons (called the electrodes) while the current is passing, and arrange the test tubes so that all of this gas will be collected. After a sufficient quantity has been collected for testing, observe the volume in each test tube, and test the larger volume for hydrogen and the smaller for oxygen.

What is the electro-positive ion in the solution? The electro-negative ion?

The electrode by which the current enters the solution is

*A suitable vessel may be made from a funnel or from the top of a bottle which has been cut off about midway of its height. Two small rods of carbon or strips of platinum foil are soldered to the ends of two copper wires. If the wires are to be soldered to carbon, the ends of the carbon rods should be heavily plated with copper from a solution of copper sulphate by the method given in the preceding exercise. The wires should be passed through a cork in the mouth of the bottle or the stem of the funnel, taking care to keep them separated. The carbons should be held in position about a centimeter apart, and the vessel should be filled with melted sealing wax, pitch, or hard paraffin to a sufficient height to cover the copper wires.

FIG. 84.

called the Anode, and the one by which it leaves is called the Kathode.

What gas is set free at the anode? At the kathode?

Electrolysis.—The method of current conduction studied in the preceding exercises is known as Electrolysis, or Electrolytic Conductivity. In electrolysis the passage of a current is always accompanied by the movement of the dissociated parts of the dissolved molecules, and the current is carried by these ions. Thus it is by electrolysis that the current passes through a voltaic cell.

Theory of Electrolysis.—It is generally believed that in any water solution which is capable of electrolytic conductivity some of the molecules are being constantly broken up into their ions, and that these ions are constantly recombining to form new molecules. This makes it necessary that there should be in the solution at all times a number of free ions, half of which are electro-positive and half electro-negative. When an electric field is established in the liquid, the positive ions move toward the negative electrode and the negative ions toward the positive electrode. These ions move but a very small distance before they recombine with other ions; but, on the whole, there is a movement of positive ions in one direction through the liquid and of negative ions in the opposite direction. When these ions come in contact with the oppositely charged electrode, they give their charges to it, or take opposite charges from it, and either combine with the electrode or with other ions of their own kind and, if gaseous, escape from the solution.

Measurement of Current Strength by Means of Electrolysis.—The phenomenon of electrolysis was

first discovered by Carlisle and Nicholson in the year 1800, but the subject of electrolytic conductivity was first fully investigated by Faraday in 1834. Faraday found that not the slightest current can pass through an electrolytic solution without the decomposition of a part of the solution. He also found that if the same current was passed through a number of vessels containing acidulated water, the amount of hydrogen and oxygen set free was the same in each vessel, regardless of the size or shape of the vessel or electrodes or of the strength of the solution. If a current after passing through a vessel of acidulated water was divided into two branches and passed through vessels of acidulated water in both branches, the total quantity of gases given off in the branches was equal to the quantity given off in the main current.

These experiments showed Faraday that the amount of decomposition in the circuit was proportional to the current, and accordingly that the quantity of gases given off in a second might be taken as the measure of the current strength.

The Voltameter. — An instrument arranged for measuring the strength of a current by the amount of chemical decomposition which it produces is called a Voltameter. The apparatus used in Exercise 115 or 116 may be used as a voltameter by weighing the copper deposited or by measuring the gases given off. The voltameter method of measuring a current is so accurate that the ampere has been defined by the amount of silver which it will deposit in one second in a properly constructed silver voltameter. The copper voltameter is also largely used, especially in technical work.

Faraday also found that if the same current was passed through a number of voltameters containing different solutions, the amount of decomposition in one was chemically equivalent to the amount of decomposition in another. Thus one gram of hydrogen is replaced in a chemical compound by 108 grams of silver or 31.6 grams of copper. If a water voltameter, a voltameter containing a solution of silver nitrate and one containing a solution of copper sulphate be connected in a line and the same current be sent through them all, when one gram of hydrogen has been set free in the water voltameter, 108 grams of silver and 31.6 grams of copper will have been deposited in their respective voltameters.

Electro-chemical Equivalents.—The electro-chemical equivalent of a substance is the amount by weight of the substance which will be set free from a solution in one second by a current of one ampere, that is, by one coulomb of electricity. The electro-chemical equivalents of the elements bear the same ratios as the combining weights of the elements when they form chemical compounds.

The electro-chemical equivalent of hydrogen is .00001038 gram. What is the electro-chemical equivalent of silver? Of copper?

Electrolytic Polarization. — It has already been mentioned that when the products of electrolytic dissociation are deposited upon the plates of a voltaic cell they may decrease the electromotive force of the cell. Thus the potential difference between zinc and hydrogen is less than between zinc and carbon, hence the current of a cell made of zinc and carbon is greatly decreased when the carbon plate becomes coated with hydrogen.

The same thing is true of zinc and carbon in a copper sulphate solution. The potential difference between zinc and copper is less than between zinc and carbon, hence the electromotive force of the cell is weakened when the carbon plate becomes coated with copper.

When a cell is weakened by the deposition of the products of electrolysis upon one or both of its plates, the cell is said to be polarized. The two similar plates in the voltameter may likewise be said to be polarized by the changes which take place on their surface during the passage of a current.

Currents due to Polarization.

LABORATORY EXERCISE 117.—Attach copper wires to two strips of sheet lead of convenient size, stand them in a tumbler of dilute sulphuric acid solution at a distance of about a centimeter from each other, and connect them to a galvanometer. Do they form a voltaic cell?

Send a current through them from two or more cells arranged as for the water voltameter. Notice carefully the direction of the current through the liquid. After the current has passed for several minutes, disconnect the battery and connect the plates again to the galvanometer and note the direction of the current. Allow the current to flow for some time. Does the cell finally run down?

Storage Cells.—The lead plates in the sulphuric acid solution form what is called a Storage Cell or Accumulator, though it does not in reality store up electricity. The lead of one plate is acted upon by the oxygen of the current, and that of the other plate by the hydrogen. The one accordingly becomes coated with lead oxide, while the oxide already formed on the surface of the other is removed by the hydrogen, leaving a clean lead surface. When the current is broken, the lead is more strongly electro-positive than the lead oxide, and it accordingly combines with the electro-negative ion of

the solution and becomes oxidized, while the hydrogen, the electro-positive ion of the solution, goes to the lead oxide plate and reduces the oxide to metallic lead. When the two plates reach the same stage of oxidation, the potential difference between them disappears, and the current ceases.

The first storage cells were made of lead plates as in the preceding experiment, but most storage cells are now made by filling a porous lead plate, called a grid, with a paste made of red lead, a lead oxide. This paste is reduced to metallic lead in one plate, and is still further oxidized in the other by the passage of the current.

Some of the ordinary voltaic cells may be used as storage cells. For example, the plates of the Edison-Lalande cell are composed of zinc and copper oxide. The hydrogen goes to the copper oxide plate and reduces it to metallic copper, after which the cell becomes useless. By sending a current through the cell in the opposite direction the copper plates could be again oxidized, but the zinc plate could not be restored to its former efficiency in this way.

Internal Resistance of Cells.—We have found in our experiments on electrolysis that an electrolytic solution offers a considerable resistance to the passage of a current, so that several cells are necessary to maintain a strong current through such a solution. The same thing is true of the electrolytic liquid in a voltaic cell. If the two plates of the cell are connected by a short copper wire or a conductor of any kind having a low resistance, they are said to be short-circuited. In this condition the principal resistance to the passage of a current is found to be in the liquid of

the cell. This resistance seems to be principally due to the resistance which the ions meet with in their passage through the liquid, and all the energy expended in driving the current through the liquid is transformed into heat.

The current which a cell will give on short circuit accordingly depends upon the electromotive force and the internal resistance of the cell. With the same metals in a given solution, the electromotive force of the cell cannot be increased, since the potential difference between large pieces of zinc and copper is the same as between small pieces. By increasing the size of the plates we may, however, increase the current strength, since we increase the number of ions which are carrying charges through the liquid, and as this increases the current strength without increasing the electromotive force, it is equivalent to decreasing R in the equation $C = \frac{\text{E.M.F.}}{R}$.

By moving the plates of the cell closer together we may also decrease the internal resistance of the cell.

The current which may be derived from a cell through an external resistance, as a long wire, is found by dividing the electromotive force of the cell by its internal resistance plus the resistance of the external conductor. Hence a cell of low electromotive force and low internal resistance, while it may give a strong current when short-circuited, cannot give a strong current through great external resistance. An Edison-Lalande cell of .8 volt E.M.F. and .04 ohm internal resistance may give on short circuit a current of 20 amperes, while a Daniell's cell of 1 volt E.M.F. and

3 ohms internal resistance can give only $\frac{1}{8}$ ampere on short circuit. Through an external resistance of 20 ohms the two cells will give currents of $\frac{1}{23}$ ampere and $\frac{1}{23}$ ampere respectively.

Grouping of Cells.—We learned in static electricity that metallic conductors when in contact with each other necessarily take the same potential; consequently when the zinc of one cell and the copper of another are connected by a wire there can be no potential difference between them. Since each plate is maintained at a different potential from the other plate in its own cell by the intervening liquid, the potential difference of the free zinc and the free copper of the two cells is twice that of the zinc and copper of a single cell. By connecting a number of cells in line in this way, we accordingly get a potential difference at the terminals which is the sum of the potential differences of all the cells in the line. Cells connected in this way are said to be joined in series.

Since the current given by the cells when joined in series must flow through all the cells, the resistance of the line of cells is likewise the sum of the resistances of the single cells. Accordingly a number of cells joined in series will give the same current on short circuit as a single cell. For example, four Daniell's cells with an E.M.F. of one volt and an internal resistance of three ohms will give when joined in series an E.M.F. of four volts and an internal resistance of twelve ohms, hence a current of one third ampere, the same current that a single cell would give. If the external resistance be great, however, then the four cells will give approximately four times the current of a single cell. Thus with an external resistance of 100 ohms, a single

cell will give a current $C = \frac{1}{103}$, while the four cells will give a current $C = \frac{4}{112}$.

Another method of connecting the cells is to join all the zincs to one wire and all the coppers to the other. In this case the E.M.F. is not increased, since the plates which are joined were all at the same potential before they were connected. The current on short circuit is increased, however, as each cell gives the same current through the connecting wire that it would give if it were not joined to the others. This method of joining the cells is accordingly equivalent to decreasing the internal resistance of the circuit. The four Daniell's cells previously considered would when joined in this way each give its original current of one third ampere, and the four together would give a current of four thirds ampere. Since this increase of current is accomplished without increasing the potential difference, it must be due to the decrease of internal resistance. The resistance of the four cells joined in this way is accordingly taken as three fourths an ohm.

Cells connected in this way are said to be joined parallel.

PROBLEMS.—What current would the four Daniell's cells joined parallel give through an external resistance of 100 ohms? What current would a single cell give through the same resistance?

How would you connect six Daniell's cells having an electromotive force of one volt and an internal resistance of three ohms so as to give a current of two amperes on short circuit? (The cells may be connected in series or parallel, or in groups of two or three parallel.)

How would you connect the same cells to give the greatest possible current through 20 ohms external resistance?

ELECTRIC RADIATION

ELECTRIC WAVES

Maxwell's Theory.—In our discussion of the pressure exerted by one charge of static electricity upon another through the intervening Ether, we saw that this pressure is analogous to that caused by a displacement in an elastic body, so that Maxwell named the property of the Ether by virtue of which the pressure is exerted the Electric Elasticity of the Ether. We also learned that when a spark discharge takes place between a positively and a negatively electrified body the intervening dielectric seems to give way to the electric pressure and allow a quantity of electricity to pass through. We also learned that the spark discharge is of an oscillatory character, so that apparently a quantity of electricity passes back and forth from one conductor to the other several times before it finally comes to rest.

Maxwell argued that if the electric pressure were, as he supposed, exerted by the elasticity of the Luminiferous Ether, such an oscillation taking place in it would set up waves which would be transmitted in all directions, like sound waves in air, and that these waves would travel with the velocity of light, since light travels by means of waves in the same medium. He showed that the time required for a spark discharge to take place was greater when a large quantity of electricity was discharged than when the quantity was small, and accordingly that the oscillations of the discharge would be slower the greater the capacity of the discharging conductor. He calculated the dimensions of conductors which would discharge with sufficient

rapidity to set up oscillations as rapid as those of light, and found that such conductors would be of about the size of the atoms or molecules of material bodies. He accordingly advanced the theory in 1876 that light waves are due to the oscillations set up by electric discharges or disturbances between the atoms of luminous bodies. This was known as Maxwell's Electromagnetic Theory of Light.

Hertzian Waves.—The waves set up in the Ether by electric discharges were experimentally discovered ten years later by Prof. Hertz, in Germany, and have since been called the Hertzian Waves. These waves have been much studied and their properties are well known. They are now coming into extensive use in "Wireless Telegraphy."

Electric Resonance.*

LABORATORY EXERCISE 118.—Two similar Leyden jars of the same capacity are set upon wooden blocks provided with upright standards. One jar, as in Fig. 85, has a strip of tin-foil about a centimeter wide pasted to the outside of the jar and reaching from the outer coating over the edge of the jar and making connection with the knob and the inner coating. This strip is cut down in one place to a width of three or four millimeters, and after it has dried a scratch is made across it with the point of a needle, taking care that the contact is broken, but leaving the edges as close together as possible.

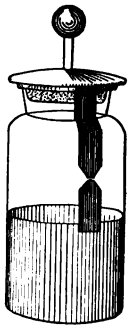


FIG. 85.

Two pieces of copper wire about five feet long are cut of equal length, and are passed through holes in the tops and bottoms of the wooden standards and are bent into similar loops, as shown in Fig. 86. One of these loops ends in a small knob, as shown in the figure, while the corresponding end of the other

* The following experiments may be used as laboratory exercises, or they may very properly be performed by the teacher before the class.

is attached to the knob of the Leyden jar upon which the tin-foil strip was pasted. The other ends of the wires are placed under the jars, making contact with their outer coatings.

Adjust the wire loops as nearly as possible alike, and stand the two jars side by side about a foot apart with their wire loops parallel. Connect the discharging knobs of the electric machine by fine wires to the jar without the tin-foil strip, joining one wire to the knob of the jar and the other to the small knob on the end of the wire loop. Separate this knob a few millimeters from the knob of the jar and turn the machine until the jar discharges by a spark between the two

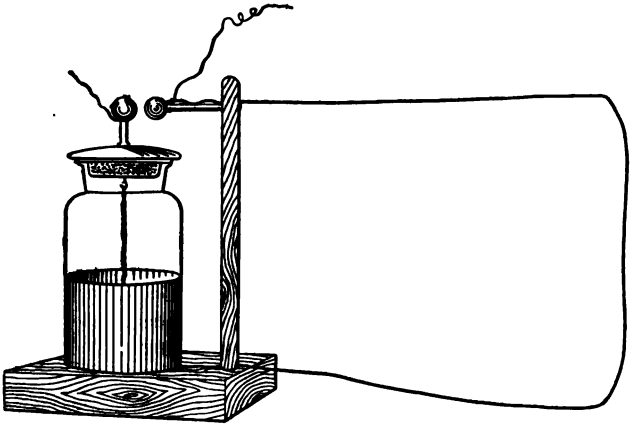


FIG. 86.

knobs. If the wires on the two jars are properly adjusted, a spark will pass across the scratch in the tin-foil of the other jar. If the spark does not appear at once, change the length of one wire slightly by pushing its end farther under the jar, or by pulling it out a little. This end should always make a good contact with the outer coating of the jar. With a little adjustment, the uncharged jar can be made to spark at every discharge of the other jar.

The two jars, like the two resonance forks used in the sound experiments, are tuned to the same period of oscillation, but while the vibration in the tuning fork is induced by air waves, the electric vibrations in the Leyden jar are induced by Ether waves. Since the oscillations set up in

one jar by the spark discharge are of the same period as those which would be set up in the other jar by a similar discharge, the Ether vibrations induce sympathetic vibrations in the other jar. This phenomenon is accordingly known as Electric Resonance.

Keeping the jars at the same distance from each other, turn one of them until the plane of its loop is at right angles to that of the other jar. In this position you will be unable to get the uncharged jar to spark.

If the Ether waves were compressional waves, the jar should spark as well in the second position as in the first; hence they are apparently waves of transverse vibration and cannot set up oscillations at right angles to their own vibrations.

The Coherer.

LABORATORY EXERCISE 119.—Take a glass tube of about a centimeter bore and six or eight centimeters long, fit the ends with corks through which copper wires can be passed, and fill the tube between the corks with brass or iron filings. Thrust copper wires through the corks and into the iron filings until their ends are one or two centimeters apart. Connect these wires in circuit with one or more voltaic cells and a tolerably sensitive galvanometer. The resistance of the filings to the passage of a current should be so great that the galvanometer is slightly, if at all, deflected.

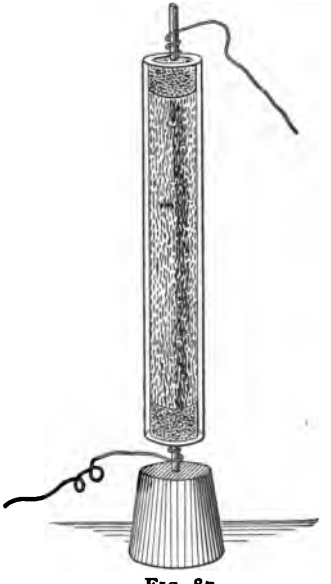


FIG. 87.

Bring an electric machine near, and pass sparks from one discharging knob into one of the wires which enters the tube. The resistance should fall so that the galvanometer is deflected through nearly 90°.

This instrument is called a Coherer. The passage of the electric discharge into the small metallic particles in the tube apparently causes them to cling together so that they make better electric contact than before.

After your coherer has become sensitive enough to allow the passage of a suitable current, increase its resistance again by tapping gently on the glass and causing the particles to separate. Then move the electric machine to a distance of a few feet from the coherer and turn the handle and cause sparks to pass between the discharging knobs of the machine. If your coherer has been properly adjusted, the galvanometer will be deflected again, showing that the resistance of the coherer has been again diminished. By a little care in the adjustment, and by using a sensitive galvanometer, the coherer will respond to a spark at a distance of several yards.

If convenient, work the electric machine on the opposite side of a stone or wooden wall and observe that the electric waves pass readily through the wall.

Wireless Telegraphy. — The coherer described above is similar to the receiver used in "wireless telegraphy." The coherer is connected between a battery and a telegraph sounder, and is attached to a long wire or other conductor suspended at some height. A similar conductor is suspended at the sending station, and is connected with the spark gap of the electric machine or induction coil. The oscillations in the receiving conductor are accordingly partly due to resonance, and they are sufficient to lower the resistance of the coherer so that a signal can be made through it. An automatic tapper jars the particles apart, so that the signal is momentary unless the instrument is sensitized by another spark.

ROENTGEN RADIATION

Electric Discharge in Rarefied Gases.—We have seen that gases at atmospheric pressure offer a very

high resistance to the passage of the electric discharge. This is not true of rarefied gases. When the air is exhausted from a glass tube until it will sustain a pressure of only two or three millimeters of mercury an electric discharge may be readily passed between two metallic electrodes sealed into the glass. When this occurs, the discharge does not pass as a spark, but the whole interior of the tube is lighted up by a glow. Tubes prepared in this way are called Geissler's Tubes.

Kathode Rays.—When the tube is more highly exhausted the glow disappears, and at a sufficiently high exhaustion a bluish light is seen to go out in

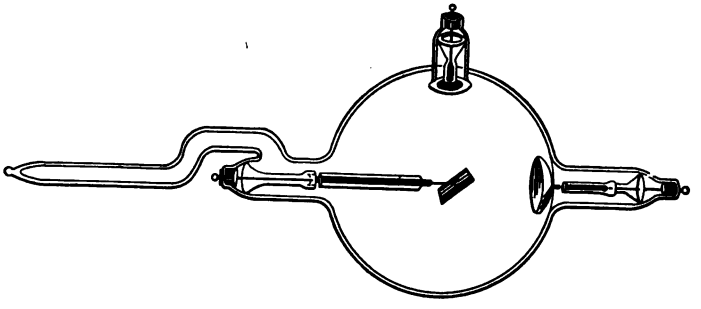


FIG. 88.

straight lines from the negative electrode, called the Kathode. This bluish light is called the Kathode Radiation. It is probably due in large part to electrified particles thrown off from the kathode by the discharge. Fig. 88 shows a tube prepared for Roentgen Radiation in which the kathode is made concave in order to focus the kathode radiation upon a platinum plate mounted in the tube.

Formation of Roentgen Radiation.—Where the kathode radiation strikes upon the walls of the tube or

upon metal plates within the tube, a form of invisible radiation is produced which was discovered by Professor Roentgen in 1895 and was named by him the X-Radiation, because its character was unknown. It is now generally called the Roentgen Radiation, after its discoverer.

Properties of Roentgen Radiation.—The Roentgen Radiation, like the Hertzian Waves, passes readily through many substances which are opaque to light. Since it cannot be seen, it can only be detected by its electrical or chemical effects. It is generally detected by its power of inducing a glow, called fluorescence, in many chemical substances, or by its effect upon a photographic plate.

If the Roentgen Radiation is allowed to fall upon a fluorescent screen prepared by coating a piece of cardboard with some fluorescent substance, it will cause the surfaces of the screen to glow with a faint light, which can be plainly distinguished in a dark room. A substance opaque to the radiation, if held between the screen and the source of radiation, will cast a shadow upon the screen, just as an opaque body held between a lighted lamp and the wall will cast a shadow upon the wall. These shadows may be observed directly upon the screen, or they may be photographed upon a sensitized plate.

Since the skin and flesh of the body are fairly transparent to Roentgen Radiation, the shadows of the bones and of opaque objects imbedded in the flesh can be observed on the fluorescent screen, hence the use of this form of radiation in surgery.

Fig. 89* is a photograph taken of an actual surgical

* Photographed by Dr. Philip Mills Jones, of San Francisco.

case. It shows the shadows of the bones of a hand in which two of the metacarpal bones are broken, and was taken through a wooden splint and bandages.

FIG. 89.

PROBLEMS.—What weight of silver may be deposited from a silver nitrate solution in ten minutes by a current of 5 amperes?

What is the strength of a current which will deposit 5.9 grams of copper in one hour?

One liter of hydrogen weighs 89.6 milligrams; what is the strength of a current which will set free one cubic centimeter of hydrogen per minute?

Five storage cells each having an electromotive force of 2 volts and an internal resistance of .1 ohm are joined in series with a copper voltameter and cause a deposition of .00984 grams of copper per minute. What is the resistance of the voltameter?

What is the current strength of four cells joined in series, each having an electromotive force of 2 volts and an internal resistance of $\frac{1}{2}$ ohm—

(*a*) When the external resistance is negligible?

(*b*) When the external resistance is 10 ohms?

(*c*) When the external resistance is 100 ohms?

Calculate the current given by the same cells through the same resistances when the cells are joined parallel.

A coil of wire having a resistance of 100 ohms is immersed in one liter of water at 20° C., and has a current of one ampere maintained in it. What will be the temperature of the water at the end of 20 minutes?

An arc light having a potential difference of 100 volts between its carbons is run by a current of 5 amperes. What horse-power does it absorb?

What is the candle-power of this arc, counting one watt per candle-power?

What is the cost of maintaining this light at 5 cents per kilowatt hour?

The resistance of a copper conductor of one square centimeter cross-section reaching from Niagara to New York would be about 80 ohms. What potential difference must be maintained at the terminals of this conductor in order for it to carry a current of 500 amperes?

What would be the loss of energy in the wire, measured in kilowatts?

What measured in horse-power?

A current of 500 amperes is transformed from a potential difference of 40,000 volts to one of 100 volts; neglecting the loss of energy in the transformer, how many amperes will it give?

PART VI

OPTICS AND RADIATION

DEFINITIONS

Origin of Radiant Energy.—We have already seen that both heat and electrical energy may be transformed into radiant energy and transmitted by the Luminiferous Ether.

Light.—That form of radiant energy which is the physical cause of our sensation of sight is called Light.

Optics.—That branch of Physics which treats of the subject of Light is called Optics.

Radiation Best Studied in Optics.—Since we have a special sense organ which enables us to recognize light, the laws of radiation may be more easily understood from the study of Optics than from any other branch of Physics.

ORIGIN OF LIGHT

Luminous Bodies.—So far as we know, light always has its source in some material body. A body in which light originates is called a Luminous Body.

PROPAGATION OF LIGHT

Transmission by Optical Medium.—It is a familiar observation that light travels in all directions from the luminous body which is its source. We also know that

it travels readily through a vacuum, as otherwise bodies in a vacuum, as the filament in an incandescent lamp bulb, would be invisible, and light could not reach us from the stars. It likewise travels readily through many material bodies.

A substance through which light can be transmitted is often called an Optical Medium, or simply a Medium. If the medium allows light to pass so readily that objects may be seen through it, it is said to be Transparent. If some light passes through it, but not enough for distinct vision, the medium is said to be Translucent. Substances which do not allow the passage of light through them are said to be Opaque.

Velocity of Light Propagation.—The velocity of light propagation through the Luminiferous Ether of the Solar System was first measured by Roemer, a Danish astronomer, at the Paris Observatory in 1676. His method may be understood from the accompanying diagram in which *S* may stand for the Sun, the circle

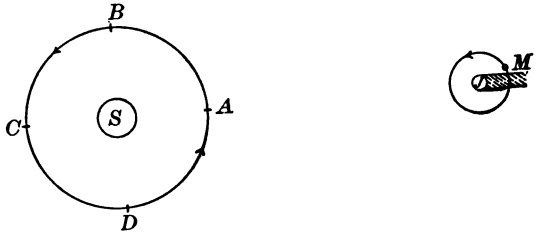


FIG. 90.

ABCD for the Earth's orbit, *J* for the planet Jupiter, and *M* for the largest of Jupiter's five moons, known as the "first satellite." This moon revolves about Jupiter and is eclipsed at equal intervals of time by passing into the shadow of the planet. The time of

rotation, and hence the period between two successive eclipses, is 48 hours 28 minutes 35 seconds. Roemer found that when the Earth was at *A* or *C* the observed time between two successive eclipses was the same, but that when the Earth was approaching Jupiter, as at *D*, the eclipses occurred at shorter intervals, and when the Earth was receding from Jupiter, as at *B*, the intervals between successive eclipses were greater than when the Earth was at *A* or *C*. Roemer reasoned from this observation that it took light an appreciable interval of time to travel the distance passed over by the Earth in the time which elapsed between two successive eclipses. By acting on this conclusion and carefully noting the time between two successive eclipses when the Earth was at *A* and neither approaching nor leaving Jupiter, the exact time at which an eclipse would occur six months later when the Earth would be at *C* was calculated. By observing the time of this eclipse six months later, it was found to occur 16½ minutes later than the calculated time, while the time between two successive eclipses was the same as when the Earth was at *A*. It was accordingly concluded that light required 16½ minutes to travel across the Earth's orbit from *A* to *C*.

Calling the diameter of the Earth's orbit 296,000,000 kilometers or 186,000,000 miles, and the time required for light to cross it 990 seconds, this calculation makes the velocity of light about 299,000,000 meters, or 188,000 miles, a second.

In more recent times several methods have been devised for measuring directly the velocity of light. As a result of many careful measurements, the velocity is now taken as about 300,000,000 meters a second.

First Law of Light Propagation.—We have already defined (page 129) as isotropic those substances in which all the physical properties are the same in all directions. Since the possibility of transmitting light is regarded as a physical property, it follows that *in an isotropic medium the velocity of light is the same in all directions from its source.* This may be regarded as the first law of light propagation.

Since all liquids and gases, as well as amorphous solids, are isotropic, the velocity of light is the same in all directions from its source in these substances.

Light Waves.—If a luminous point should suddenly come into existence in an isotropic optical medium, the illuminated region about the point at any instant after the origin of the light would be a sphere with the luminous point as its center. In one second after the origin of the light this illuminated region would be a sphere with a radius of 300,000,000 meters. In one three-hundred-millionth of a second it would be a sphere with a radius of one meter. A disturbance propagated as a constantly enlarging sphere is called a Spherical Wave. We may accordingly state the first law of light propagation in other words by saying, *Light is propagated in spherical waves.*

Wave-front.—The term Wave-front is used as in Sound. Thus *the whole surface of a spherical wave at any given instant of time is called a Wave-front.*

Law of Decrease of Intensity.—If the surface of a spherical wave of light has at all times the same total illumination, then the intensity of illumination will decrease as the area of the wave-front increases. Since the surface of a sphere increases as the square of its radius, *the intensity of illumination upon the spherical*

wave-front of light must decrease as the square of the radius of the spherical wave increases.

If a screen be placed near a source of light to intercept a portion of the wave-front, the intensity of illumination upon the screen will vary with its distance from the source of light. At a distance of two feet from the source it will have only one fourth the intensity of illumination that it would have at a distance of one foot. *The illumination upon the screen will decrease as the square of its distance from the source of light increases.*

PHOTOMETRY

Definitions.—That branch of Optics which is concerned with the measurement of light intensities is called Photometry. An instrument used to compare intensities of illumination is called a Photometer. Many different forms of photometer are made. Some of the more common ones are described below.

The Rumford Photometer.—Rumford's Photometer is made by placing an upright, opaque rod, as a lead-pencil, at a distance of 8 or 10 centimeters in front of a vertical sheet of unglazed white paper, which should be mounted against a board. This apparatus is set up in a dark room and a lighted candle or lamp is placed in front of it so that the shadow of the rod will fall upon the paper. The whole paper with the exception of this shadow will be illuminated by the light. If another lamp or candle be placed beside the first one, two shadows will be thrown upon the screen, but neither of them will be as dark as the first one, since the shadow cast by each light will be illuminated by the other light. All the rest of the screen will be illuminated by both

lights. If the lights are placed so that the shadows are very near together, it will be possible to adjust the distances of the lights so that the two shadows seem to be equally dark. This will be the case when each shadow is equally illuminated by the other light. The intensities of illumination of the two lights upon the screen will then be the same, and the intensity of illumination of either shadow will be just half the intensity upon the rest of the screen.

The Bunsen Photometer.—Bunsen's Photometer is made by putting a drop of grease on a piece of unglazed white paper and placing the paper vertical between the two lights to be compared, with one face turned toward each light. The grease spot on the paper is more transparent than the rest of the paper and allows part of the light to pass through the paper. If the paper be lighted from only one side, the grease spot will seem darker than the rest of the paper when looked at from the light side and lighter when looked at from the dark side. When both sides of the paper are equally illuminated so that as much light passes through the paper from one side as from the other, the grease spot will appear of the same brightness as the rest of the paper, and the relative intensities of the two lights can be calculated from their distance from the paper. In practice, the grease spot cannot be made of the same brightness as the rest of the paper on both sides at once, since some of the light is absorbed in passing through the paper. When the proper adjustment has been made, the grease spot will accordingly appear a little darker than the rest of the paper on both sides.

The Joly Photometer.—This photometer is made by cutting out two little slabs of paraffin about a centi-

meter thick and of convenient length and width (5 centimeters long and 2 centimeters broad gives a convenient size), and by warming one side of each and sticking them together with a piece of black paper or tin-foil between them to form an opaque partition. The two slabs should be of the same thickness.

This instrument is placed between the two lights whose intensities are to be compared, with the opaque partition vertical, like the screen of the Bunsen Photometer. The translucent slabs of paraffin are then each illuminated by one light and shielded from the other. When they are equally bright as seen from their edges, the adjustment is complete, and the distances of the lights may be measured.

Comparison of Photometers.

LABORATORY EXERCISE 120.—Place two lighted candles about a meter apart, and place a Bunsen or Joly photometer between them, adjusting it so that both lights give equal illumination at the photometer. Measure the distance to one of the candles, and without disturbing anything else remove this candle and replace it where it seems to give the same illumination as before. Measure the distance again, and see how nearly you have placed it in the original position. Repeat three or four times, and find the greatest variation between your settings.

Make the same test with one or more of the other photometers and decide which is the more sensitive instrument.

What part of the whole distance of the candle from the photometer was uncertain in your settings?

What percentage of the whole distance was uncertain?

To Test the Law of Inverse Squares.

LABORATORY EXERCISE 121.*—Set up a photometer in a dark room, place a lighted candle about 50 centimeters from it and place four lighted candles mounted on a block so that

* Any of the above photometers may be used in this experiment. It may be well to have different members of the class use different instruments.

they will all be in a line perpendicular to the photometer screen and at such a distance from the photometer that their illumination at the instrument will be equivalent to that of the single candle. Measure this distance to a point between the two inner candles. Repeat with the single candle 25 centimeters from the photometer.

What is the ratio between the distances of the two sources of light? What should be the ratio according to the law of inverse squares? (It is evident that in this experiment the four candles should be like the single candle, and their wicks should all be trimmed to as nearly the same height as possible.)

How far from the screen should two candles be placed to give the same illumination as one candle at 25 centimeters? Place two candles at this distance and compare them with the single candle.

Are the variations of your results from the law of inverse squares greater than the variations between single comparisons of two lights? If so, what may be the possible causes of error?

Candle-power of a Lamp.

LABORATORY EXERCISE 122.—The intensity of different artificial sources of light is generally measured in candle-powers. A lamp is said to be of ten candle-power when it gives as much light as ten standard candles.*

Using an ordinary candle as a standard, determine the candle-power of a kerosene lamp. Make five determinations with the candle at different distances and take the mean of the results.

Letting C represent the illuminating power of a lamp, c that of a candle, and D and d the corresponding distances from a screen which is equally illuminated by both, give an equation for the candle-power of the lamp $= C$ in terms of c, D, and d.

* The standard candle is different in different countries. In England it is a sperm candle weighing six to the pound and burning at the rate of 120 grains per hour. In Germany it is a paraffin candle of uniform diameter of two centimeters, with its wick trimmed so that the flame is five centimeters high. The British standard is generally used in this country. No candle is an accurate light standard, as the light constantly fluctuates in brightness.

(It is advised that students test the candle-power of the lights used in their homes by means of the Joly photometer.)

What difficulty appears in comparing a candle with a lamp which gives a very white light?

PROBLEMS.—A standard candle is placed 2 feet from a screen and a lamp of nine candle-power is placed 3 feet from the screen. Compare their illuminating power on the screen.

A standard candle and a 16-candle-power lamp are placed 2 meters apart. Where between them must a Joly photometer be placed to show equal illumination on both sides?

In measuring the distance of a candle from a Rumford photometer, do you measure from the candle to its shadow, or to the shadow which it illuminates?

Two 8-candle-power lamps are placed on opposite sides of a Bunsen photometer screen, one 20 centimeters and the other 30 centimeters from the screen. Where must a standard candle be placed to make the illumination on both sides of the screen the same?

REFLECTION OF LIGHT

Reflective Power of Various Bodies.—Place an open book with its back to a window or other source of light so that the printed pages will be in the shadow. Try to reflect light upon the pages by means of a mirror. By means of a piece of window glass. Of white paper. Of black paper. Do these bodies reflect light? Do they reflect equally well?

Luminous bodies are made visible by the light which they emit; non-luminous bodies by the light which they reflect. A body which reflects no light to the eye is invisible. Its surface appears black.

Regular and Irregular Reflection.—There are two ways in which bodies may reflect light. They may reflect the light so that we can see plainly the surface of the body itself, as is the case with white paper, or

they may reflect the light so that we see the original source of light instead of the reflecting body, as in reflection from a mirror. In the former case light goes off in all directions from each point in the reflecting body as from an original source of light; in the latter case the light is reflected only in a definite direction from each part of the reflecting surface. The former is called irregular or diffuse reflection; the latter is called regular or mirror reflection. It is only by diffuse reflection that non-luminous bodies are made visible. A perfectly reflecting mirror surface would be invisible to us, and we would see in it only the bodies whose light it would reflect to our eyes.

Effect of Polishing Surface of Reflecting Body.—In general, when light falls upon a non-luminous body part of it is reflected. The more highly polished the surface of the reflecting body, the greater the proportion of the light which is regularly reflected. Almost any surface may be made a mirror surface by sufficient polishing.

Huyghens' Construction for Advancing Wave-front.—In order to understand the nature of reflection it is necessary to consider more fully the method of light propagation.

The method of wave propagation in an elastic medium such as the Luminiferous Ether is supposed to be is by each point on the surface of the spherical wave becoming the center of disturbance from which a secondary spherical wave is sent off. The points in the surface of these secondary waves become new centers of disturbance from which other waves start, and so on indefinitely. Since all these secondary waves increase at the same rate, the resulting surface

tangent to all of them is itself spherical and becomes the main wave-front which we consider in light propagation.

The method of wave propagation just described may be better understood from a consideration of Fig. 91. —If S represent a source of light, the circle WF will represent a section of the spherical wave-front at a given instant of time. If the points a, b, c, etc., in the main wave-front be regarded as centers of spherical waves, the wave-fronts of these spherical waves will at another given instant of time combine to form a new wave-front, as $W'F'$. This method of drawing the projection of an advancing wave-front is known as Huyghens' Construction.

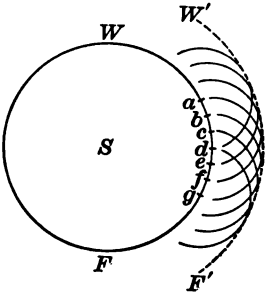


FIG. 91.

While these secondary wave-fronts are in reality immeasurably small, we can use them in projecting a wave-front as if they were of sensible size. Thus in the figure we may project secondary wave-fronts from a, b, c, etc., with any desired radius, and the resulting circle tangent to the secondary wave-fronts will accurately represent a projection of the main wave-front at some given instant of time. It is by means of these secondary wave-fronts that we are enabled to project the main wave-front after it has been reflected from a given surface.

REFLECTION FROM PLANE SURFACES

Reflection from Plane Mirror.—In Fig. 92 let *MR* be the trace of a mirror surface and *S* a source of light. The dotted line *ABC* will then represent a section of a wave-front from *S* as it would have been at a given instant with the mirror removed. Since the light is reflected from *MR*, each point on the surface of *MR* may be regarded as the center of a secondary wave moving back toward *S*. The radii of these waves may be known if we know the relative velocities of the

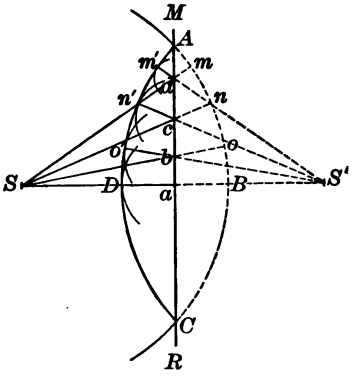


FIG. 92.

incident and reflected light. If the velocity of the reflected light be taken the same as the velocity of the incident light, the secondary wave from *a* will have returned to *D* in the time which would have been required for the advancing wave to reach *B*. The radius of the secondary wave from *a* will accordingly be *aB*. In the same way the radius of the secondary wave from *b* will be *bo*, from *c*, *cn*, and the like.

Drawing these secondary wave-fronts, the curved line *ADC* which is tangent to all of them will represent a projection of the main, reflected wave-front.

Draw a figure showing the projection of a spherical wave-front reflected from a plane mirror surface, as above, and show by construction that the reflected wave-front is also spherical and has its center at a point S' as far back of the mirror as S is in front.

Virtual Image by Reflection from Plane Mirror.—To an observer whose eye receives a part of the reflected wave-front the source S will appear to be back of the mirror at S'. The point S' is accordingly called the virtual, or apparent, image of S. It is called the virtual image because in reality there is no source of light back of the mirror.

To Locate the Virtual Image of a Plane Mirror.

LABORATORY EXERCISE 123. (One or all of the following methods may be used.)

(1) A piece of mirror about five or six inches long and having at least one straight edge has several ink lines drawn perpendicular to the straight edge and about an inch apart. Place the mirror on the straight edge on a sheet of paper, resting it against a block or other support so that it will stand upright. The ink lines will then be vertical. Draw a pencil line on the paper showing the edge of the mirror and mark with the pencil point the foot of each ink line upon the paper. Thus in Fig. 93 let *MR* represent the trace of the mirror edge and L_1, L_2, etc., the positions of the ink lines.

Stick a pin upright in front of the mirror, as at *P*. Then holding the eye near the paper, stick other pins, as P_1, P_2, etc., where they will appear in straight lines with the ink marks L_1, L_2, etc., and the image of *P*. Remove the mirror, and by means of a ruler and pencil draw the straight lines P_1L_1, P_2L_2, etc., producing them back of the surface of the mirror until they meet. If carefully drawn, they will all meet at one point back of the mirror where the image of *P* seemed to be. Let *Q* represent this point of

intersection and determine by measurement if it lies in a perpendicular from P through the mirror, and is as far back of the mirror as P is in front.

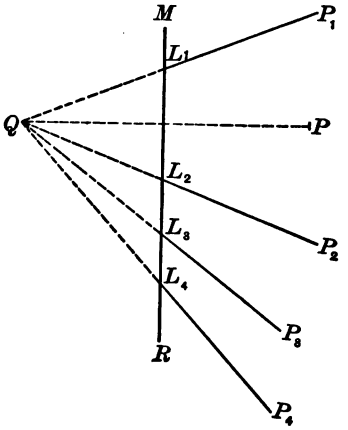


FIG. 93.

(2) Place a mirror MR upright on a sheet of paper, as before. Place a lighted candle at C and stick two hat-pins or knitting-needles upright at P_1 and P_2.

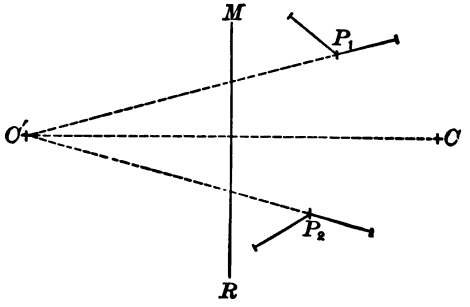


FIG. 94.

Each of these pins will have two shadows, one caused by the candle and the other by the reflected light from the mirror. Lay a ruler along the shadows and trace them upon

the paper. One pair of these lines produced will meet at the candle and the other pair at its virtual image back of the mirror. Locate this image, and answer the question as above.

(3) Set a pane of glass vertical in a darkened room and place a lighted candle in front of it. Set an unlighted candle back of the glass so that when seen through the glass it appears to coincide in position with the image of the lighted candle. Determine as above the position of the image relative to the surface of the glass.

As a result of your experiments, state the law of location of a virtual image seen by reflection from a plane mirror. Thus, A source of light in front of a plane mirror has its virtual image, etc.

Can you conclude from the location of this image whether the incident and reflected lights travel with the same velocity?

Referring to Fig. 92, if the velocity of the incident light were greater than that of the reflected light, would the reflected wave-front be more or less convex than the incident wave-front? Would this make S' appear nearer to or farther from the mirror than S?

Since only a portion of the incident light is reflected, the

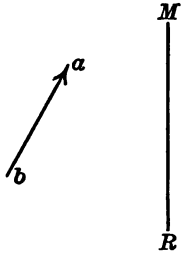


FIG. 95.

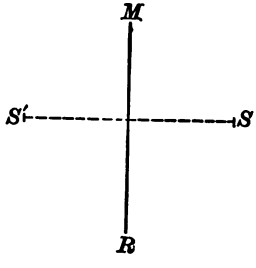


FIG. 96.

intensity of the reflected light is less than that of the incident light. Does the velocity of light apparently depend upon its intensity?

Give a rule for locating the virtual image of a point as seen by reflection from a plane mirror.

Give a rule for locating the image of an object composed of many points.

Letting *MR*, Fig. 95, represent the projection of a mirror surface, draw the image of the arrow *ab* in the position in which it will appear. How will the object and its image compare in size?

Letting *S*, Fig. 96, represent the location of a source of light and *S'* its virtual image as seen in the plane mirror *MR*, prove by Geometry that lines drawn from *S* and *S'* to any point in the mirror surface make equal angles with *MR*.

Draw a perpendicular through *MR* at the point of meeting of the two lines, and prove that the lines from *S* and *S'* make equal angles with this perpendicular.

The Method of Rays.—In the earlier theory of Optics, known as the Emission Theory, light was supposed to consist of small particles of a peculiar substance sent out from the luminous body. These particles were supposed to travel in straight lines through an isotropic medium, but to have their direction changed by reflection or by passing from one medium into another.

The paths followed by these particles were called Rays. A number of parallel rays were called a Beam, and a number of diverging or converging rays were called a Pencil.

We now know that no such particles exist, but the terms ray, beam, and pencil of light are still used. Thus a straight line drawn from a luminous point to the surface of its spherical wave is still called a ray. It is, in fact, a radius of the spherical wave.

In the language of rays, we see a luminous or illuminated point by means of a diverging pencil of rays which enter the eye from that point. As a matter of fact, we see the point by means of a small circular area of its wave-front which enters the pupil of the eye.

The radii drawn from the visible point to this area of the wave-front are the rays which make up the diverging pencil spoken of in the language of the Emission Theory. Thus in Fig. 97 the radii *Sa*, *Sb*, and the

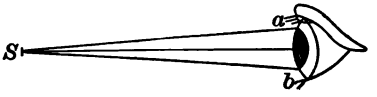


FIG. 97.

like, drawn from *S* to the pupil of the eye may represent the diverging pencil of rays by which we are said to see the body.

In the case of reflected light, a small segment of the wave-front enters the eye after its direction has been changed by reflection. Thus if *MR*, in Fig. 98, repre-

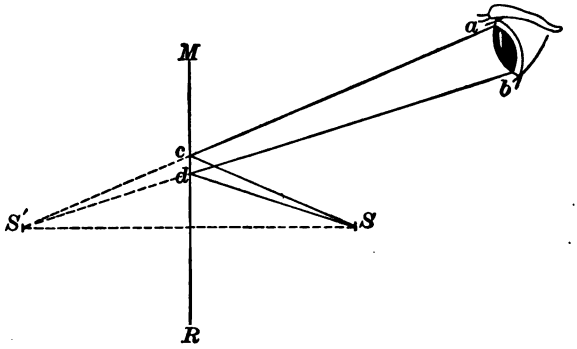


FIG. 98.

sent the reflecting surface, *S* the source of light, and *S'* its virtual image, the segment of the wave-front entering the eye appears to have its source at *S'*, and the pencil of rays seems to be *S'ca*, *S'db*, etc., instead of the broken lines *Sca* and *Sdb*.

In the language of the older Optics, the rays were bent at the surface of the mirror. The rays *Sc* and *Sd* were called incident rays, and the rays *ca* and *db* were called reflected rays. The oldest known law of reflection and the one upon which the Geometrical Optics of 2000 years ago was based may be stated as follows: *The incident and reflected rays make equal angles with a perpendicular to the mirror at the point of reflection.* Prove this proposition geometrically by the use of Fig. 99, letting *i* equal the angle of incidence and *r* the angle of reflection.

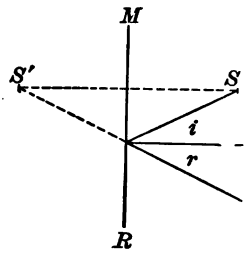


FIG. 99.

Multiple Reflection by a Mirror.—Set a pane of thick glass on edge and note that two images of a lighted candle may be seen by reflection from it. One of these reflections takes place when the light wave enters the glass from the air, and the other when the light wave emerges from the glass into the air again. In a very highly polished glass plate several images may be seen by reflection of some of the light at each emergence from the glass.

REFLECTION FROM CURVED SURFACES

Projection of a Wave-front Reflected from a Curved Surface.—The method of projecting a reflected wave-front by means of its secondary wave-fronts enables us to determine the shape of a wave-front reflected from a surface of any curvature.

The only curved reflecting surfaces usually considered in an elementary study of Optics are spherical surfaces.

Reflection from Convex Spherical Surfaces.—In Fig. 100 is shown the projection of a spherical wave-front from the point S after reflection from the convex spherical mirror MR. It will be seen that the reflected wave-front BFD is more convex than the incident wave-front $ABCDE$, and that S', the virtual image of S, is much nearer the mirror surface than S.

Draw on a conveniently large scale the projection of a spherical wave-front reflected from a convex spherical surface, as in Fig. 100, and determine by construction whether the reflected wave-front is perfectly or only approximately spherical.

Will all parts of this reflected wave-front seem to come from the same point, S'?

Will the virtual image of the point S be a point or a blur?

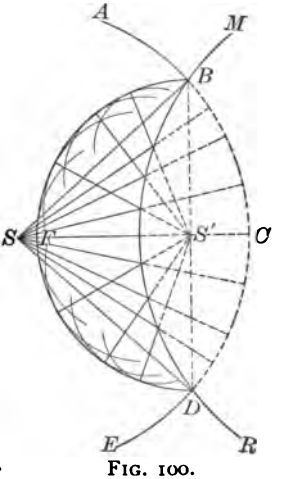


FIG. 100.

Images Seen by Reflection from a Convex Surface.

Observe the images of various objects seen by reflection from a polished metal ball or other convex, spherical surface.

Are the images nearer to or farther from the reflecting surfaces than the objects?

Are they larger or smaller than the objects?

Are they erect or inverted?

Look at the image of your face in such a mirror. Is the image distorted?

Reflection of Plane Wave-front from Convex Spherical Surface.—We have seen that the wave-front of the sunlight at the Earth is the surface of a sphere of 93,000,000 miles radius. Such a surface cannot be distinguished from a plane surface, and we accordingly

speak of the sunlight as having a plane, or flat, wave-front.

In Fig. 101 let *MR* be a convex spherical mirror and *WF* a plane wave-front advancing from left to right, the dotted line representing the position which the wave-front would have occupied with the mirror removed. Several of the radii to the plane wave-front are drawn, and the secondary wave-fronts from the points where these radii meet the mirror surface. The reflected wave-front will be tangent to these secondary wave-fronts.

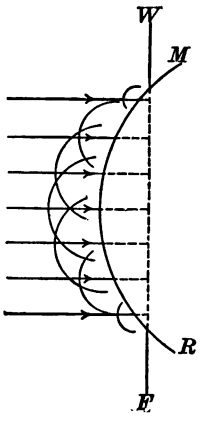


FIG. 101.

Draw the figure to a convenient scale, including the projection of the reflected wave-front, and determine whether this wave-front is spherical.

Locate the center of curvature of the mirror and the point from which the reflected wave-front seems to diverge. Measure the distance back of the mirror to each of these points and determine whether any simple relation exists between these two distances.

How should the image of the Sun appear when seen by reflection from the convex surface of a spherical mirror?

How far back of the mirror surface should the image appear?

Observe the image of the Sun in such a mirror and determine whether your conclusions are verified.

Reflection from Concave Spherical Surfaces.—We have seen that reflection from a convex surface always makes the wave-front more convex than the incident wave-front. In reflection from a concave surface the opposite is true. Thus the reflecting surface may be said to impress its own form upon the wave-front.

In Fig. 102 let *WF* be a wave-front from *S* reflected from the concave surface *MR*. It will be seen from the projection that the reflected wave-front is much less convex than the incident wave-front. It will also be seen that the reflected wave-front, if drawn tangent to the secondary reflected wave-fronts, is not perfectly spherical.

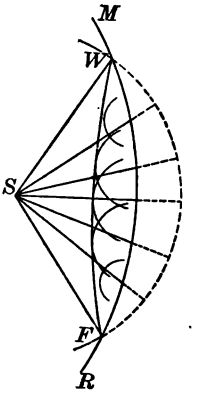


FIG. 102.

Since reflection from a concave surface renders the reflected wave-front less convex, it follows that a plane wave-front reflected from a concave surface will be made concave by reflection.

If the reflecting surface impresses its form upon the reflected wave-front, a plane wave-front reflected from a concave spherical surface should become a spherical, concave wave-front.

Since a convex wave-front grows larger as it advances, a concave wave-front should contract as it advances, and if it is a spherical, concave wave-front, it should contract to a point. A portion of the Sun's wave-front reflected from a concave, spherical mirror should accordingly contract toward a point.

Contraction of Concave Wave-front.

LABORATORY EXERCISE 124.—Allow a beam of sunlight to pass through a circular hole five or six centimeters in diameter and to fall upon a spherical, concave mirror. By tapping together two blackboard erasers above the beam and thus filling the air with particles of chalk dust or by filling the air with smoke the path of the sunbeam can be traced through the room. Turn the mirror so that the reflected beam will make an angle with the incident beam, and try to make its path visible by means of the chalk dust or smoke.

Does the reflected beam contract to a point? What must be the shape of its wave-front when it is first reflected from the mirror?

What must be the shape of its wave-front after it has passed the point of greatest contraction?

Hold a piece of paper in the path of the reflected beam and at different distances from the mirror. Where is the intensity of the illumination upon the paper greatest? Are the heat effects also more intense at this point?

Focus of Concave Wave-front.—The center to which a concave wave-front contracts is called its Focus.

Focal Length of Concave Mirror.—The distance from a concave mirror to the point at which a plane wave-front will be brought to a focus is called the Focal Length of the mirror.

Measure the focal length of the mirror used to bring the sunlight to a focus.

Relation of Focal Length to Radius of Curvature.—By remembering that lines drawn from an object and its image make equal angles with the reflecting surface, or, in the language of rays, that the angles of incidence and reflection are equal, we may establish by Geometry a relation between the focal length and the radius of curvature of a concave, spherical mirror.

Thus in Fig. 103 let C represent the center of curvature and F the focus for a plane wave-front (called the Principal Focus) of the mirror MR. If AB represent an incident ray parallel to CE, PD will represent the reflected ray from the point B. Since CB is a normal to the reflecting surface, angle ABC = angle i and CBF = angle r. We accordingly have the following relations between the angles shown in the figure: $i = r$; $i = a$; hence $a = r$, and triangle CBF is isosceles and side CF = side FB. If B be taken very

near E, the center of the mirror, $FB = FE$, nearly, and the focal length FE is approximately half of CE. It is accordingly customary to regard the focal length of a concave mirror as one half its radius of curvature.

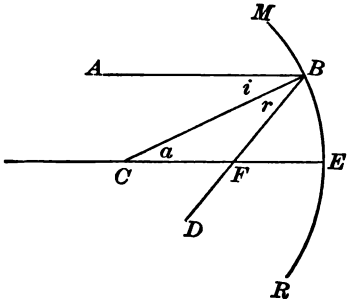


FIG. 103.

Spherical Aberration.—We have seen that a plane wave-front reflected from a concave spherical mirror is not made perfectly spherical by reflection, hence it will not all contract to the same focus. This can also be seen from Fig. 103. Since BF always equals CF, the farther the point B is taken from E the nearer the point F will approach the mirror. Accordingly, the parts of the wave-front which fall upon MR farthest from E will be brought to a focus nearest to the mirror. This defect in the concave, spherical mirror is known as Spherical Aberration.

Does the convex, spherical mirror also have spherical aberration?

Real and Virtual Images in Concave Mirrors.—In the case of the spherical wave-front reflected from the concave mirror in Fig. 102, it will be seen that the virtual image of S is back of the mirror much farther than S is in front. We have seen that a plane wave-

front after reflection from a concave mirror does not appear to come from a point back of the mirror at all, but that it contracts to a point in front of the mirror. The focus of the plane wave-front may accordingly be regarded as a *real* image of the source of light, in distinction from a *virtual* image which seems to exist back of the mirror.

Referring again to Fig. 103, it will be seen that if F be taken as the source of light, the reflected rays from the mirror will be parallel; or, in other words, if a spherical wave have its source at F, it will become a plane wave by reflection from the mirror.

If C, the center of curvature of the mirror, be taken as the source of light, the wave-front will be of the same curvature as the mirror, it will strike all parts of the mirror surface at the same time, and will be reflected without changing its curvature. It will, however, be concave after reflection, and will have its focus at the same distance as C from the mirror.

A spherical wave from a point farther from the mirror than C will be less convex at the mirror than a wave from C, and will accordingly be brought to a focus at a point nearer the mirror than C, or between C and F. Any source of light at a finite distance greater than the radius of curvature in front of a concave, spherical mirror will accordingly have a real image in front of the mirror at a distance greater than the focal length of the mirror.

Fig. 104 represents a spherical wave-front WF from S reflected from the concave mirror MR, whose center of curvature is at C. On the assumption that the reflected wave-front is spherical (which is only approximately true), it will have its center at S'. It will be

seen that S' lies farther from the mirror than F_1, which represents the principal focus of the mirror.

Accordingly, any source of light on the principal axis of the mirror outside the center of curvature will

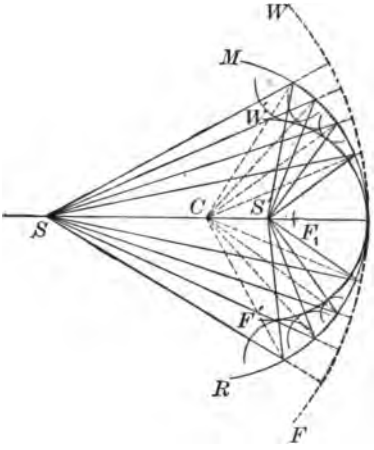


FIG. 104.

have a focus between the center of curvature and the principal focus of the mirror.

State the corresponding law for a source of light between the center of curvature and the principal focus.

Conjugate Foci.—The points S and S' are called Conjugate Foci, since if either of them is taken as a source of light, the other becomes the focus. A source of light between the principal focus and the mirror will seem to have a conjugate focus back of the mirror, but in this case the focus is virtual and not real.

Since the conjugate focus of a source of light may be regarded as the image of that source, we should have both real and virtual images formed by reflection from a concave mirror. We have already seen the image

of the Sun formed by reflection from a concave mirror. We will now try to project real images of other objects in the same way.

Experiments with Concave Mirror.

LABORATORY EXERCISE 125.—Stand in front of a window with a concave mirror, and try to project an image of the outside landscape or the clouds upon a piece of opaque white paper held between the mirror and the window.

Move farther back and try to project an image of the window upon the paper screen.

Place a lighted candle or lamp in a darkened room and try to project its image upon the screen. What peculiarity do you notice in the images formed by reflection from a concave mirror?

Fix the mirror, and find a position for the candle and screen where the image of the candle will be as distinct and sharply defined as possible, then, without disturbing the mirror, change positions with the candle and screen. Is a clear image formed in the new position?

What names do you give to the positions of the candle and screen?

In which case is the image larger than the object? Tell how to place an object in order to have an enlarged image of it reflected from a concave mirror.

Place the candle so that you can see its virtual image in the concave mirror. How does this virtual image differ in appearance from a real image formed by the mirror? How does it differ from the virtual image seen by reflection in a convex mirror?

Place the candle in a position in front of the mirror where neither a real nor a virtual image of it is formed by reflection. What is the shape of the reflected wave-front in this case? How can you measure the focal length of the mirror from this experiment? Tell where to place the lamp of a locomotive headlight with reference to its reflector.

Keeping the candle and screen at equal distances from the mirror, move them to a position where a sharp image will be formed upon the screen, and, by means of this position, measure the radius of curvature of the mirror. What of the relative size of the object and image in this position?

REFRACTION OF LIGHT

Definition.—The change in the direction or the shape of a wave-front in passing from one medium into another is called Refraction.

Refraction at Plane Surface.

LABORATORY EXERCISE 126.—Place a glass cube with faces two or three inches square upon an ink line drawn upon a piece of paper so that part of the line only is covered by the glass. Look downward through the cube at the ink line. Does the part seen through the glass seem nearer to or farther from the eye than the part seen through the air only?

In the experiments on reflection we saw that the effect of making a wave-front more convex was to make its apparent source seem nearer to an observer than its real source, and *vice versa*. In the experiment with the glass cube, is the wave-front of light apparently made more or less convex on emerging from glass into air?

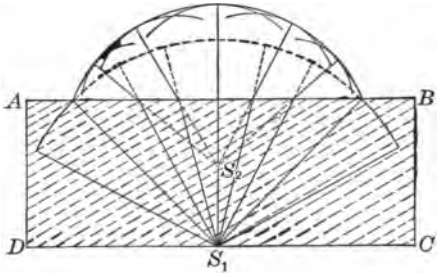


FIG. 105.

In Fig. 105 is shown the change in shape of a wave-front from S_1 in passing from one medium into another in which its velocity is increased one half. The effect of this increased velocity is to make the wave-front more convex in the new medium, and to change the apparent position of the source of light from S_1 to S_2.

Is the velocity of light greater or less in glass than in air?

Place a coin in a tea-cup or other vessel, and standing so

that the coin is just hidden from view by the edge of the vessel, pour water into the vessel. Does the coin appear to rise into view? Is the wave-front of light made more or less convex by passing from water into air? Is the velocity of light in air greater or less than in water?

Draw the projection of a spherical wave-front passing into a plane-faced medium in which its velocity is decreased one half.

To an observer immersed in water would an object in the air seem nearer or more distant than the real object?

In Fig. 105 those radii of the refracted wave-front which are oblique to the surface of separation of the two substances seem bent at this surface. Accordingly, a ray of light is said to be bent in passing obliquely from one medium into another in which its velocity is changed. When the velocity is increased, is the ray bent toward or from a perpendicular to the refracting surface at the point of emergence? Draw the ray by which you may be said to see the coin in the vessel of water.

Hold a straight rod, as a lead-pencil, about half under water and explain the apparent bending of the rod at the surface of the water.

To a person immersed in the water how would the rod seem bent at the surface of the water?

To Find the Relative Velocities of Light in Air and Glass.

Laboratory Exercise 127.—A thick glass plate with plane-parallel sides or the glass cube used in the previous exercise should have two ink lines drawn on opposite faces and parallel to diagonally opposite edges. Lay the glass plate on the face to which the lines are drawn perpendicular and, with a pencil, mark the outlines of the plate and the positions of the ink lines, as in Fig. 106, in which S and R show where the feet of the ink lines meet the paper.

Place the eye on a level with the glass, and looking through it from R to S, stick a pin upright in the paper, as at P, where it will appear in the same straight line with R and S. Remove the glass and draw the lines SR and PR, producing PR through R until it reaches nearly to the line AC. Draw SN perpendicular to the two opposite faces, AB and CD.

If we now consider a light wave from the source S, its apparent source as seen from the position P will be S'. Using S as a center, draw the arc RM. This will represent the form which the wave-front would have had at the instant

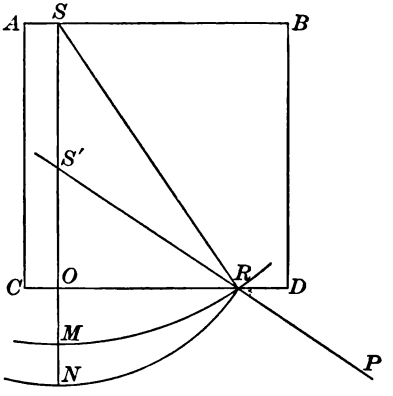


FIG. 106.

of reaching R if its velocity in air had been the same as in glass.

With S' as a center, draw the arc RN. This will represent the part of the wave-front in air at the instant when the part in glass reaches R. It must be, then, that the wave-front in air has advanced from O to N in the time which would have been required for it to advance from O to M in glass. Accordingly, the velocity in glass is to the velocity in air as OM is to ON.

Measure the distances OM and ON, and tell how the velocity in glass compares with the velocity in air.

From your measurements, what is the velocity of light in glass in miles per second? In meters per second?

Refractive Index.—The velocity of light in air divided by its velocity in any given substance is called the Refractive Index of that substance. Thus the refractive index of glass is ON divided by OM.

Calculate the refractive index of glass.

The refractive index of water is 1.33; what is the velocity of light in water?

Angle of Refraction.—If in Fig. 106 a perpendicular be drawn through CD at R, the angle made with this perpendicular by SR is the angle of incidence, and the angle made by RP and the perpendicular is the angle of refraction.

It will be seen that when a ray of light passes obliquely from one medium into another in which its velocity is increased, the angle of refraction is greater than the angle of incidence. If P be taken as the source of light, instead of S, the angle made with the perpendicular by SR becomes the angle of refraction, which in this case is less than the angle of incidence.

If the refractive index of water is 1.3 and of glass is 1.6, how will a ray of light be bent in passing from water into glass?

REFRACTION AT CURVED SURFACES

Refraction of Spherical Surface.—In Fig. 107 is shown the projection of a spherical wave-front, WF, from source S refracted at the spherical surface of a medium in which its velocity is decreased one third, as in the case of a light wave entering a spherical glass surface from the air. It will be seen that the center of the wave-front WF first enters the refracting surface and is retarded more than the edges, hence the section of the wave-front which enters the refracting medium is rendered less convex by refraction.

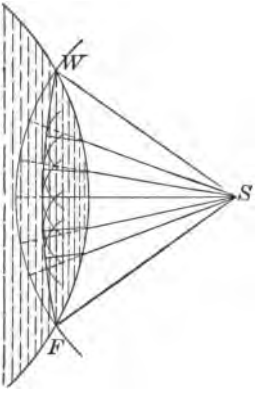


FIG. 107.

Since the convexity of a wave-front is decreased by

refraction upon entering a convex, spherical surface in which its velocity is decreased, a plane wave-front will be rendered concave by refraction at such spherical surface.

Lenses.—A portion of a transparent, refracting substance bounded by two surfaces at least one of which is spherical is called a Lens.

The six principal forms of lenses are shown in Fig. 108. Beginning with *A*, they are named as follows:

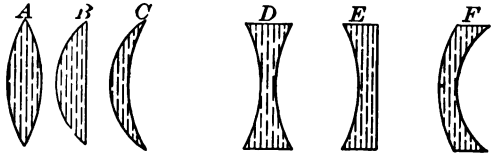


FIG. 108.

Double-convex, Plano-convex, Convex-meniscus, Double-concave, Plano-concave, and Concave-meniscus.

The three first named are also called converging lenses, because a wave-front is made less convex by passing through them. This follows from the fact that these lenses are thicker in the middle than at the edges, and hence the central part of the wave-front which passes through them is retarded more than the edges. The concave lenses, on the other hand, retard the center of the wave-front less than the edges, hence these lenses render the wave-front more convex on its passage through them and are accordingly called diverging lenses. Thus the rays of light (which are always normals to the wave-front) are made to converge by passing through a convex lens, and to diverge by passing through a concave lens.

Since a plane wave-front is made concave by passing

through a convex lens, and convex by passing through a concave lens, a convex lens should bring a plane wave-front to a focus, while a concave lens should make it appear to diverge from a point on the same side of the lens as the source of light.

Refraction by a Convex Lens.

LABORATORY EXERCISE 128.—Hold a converging lens* in the path of a beam of sunlight and determine the point at which the sunlight is brought to a focus. This point is called the principal focus of the lens. Measure the focal length of the lens.

IMAGES FORMED BY REFRACTION IN A CONVEX LENS

Place a convex lens at some distance from a window and project an image of the window on a piece of white paper or ground glass. Can you project an image of the outside landscape?

Place a lighted lamp or candle in a dimly lighted room and by means of a convex lens project its image upon a screen. Find the position for the lamp and screen which gives the clearest possible image, then leaving the lens in position, change places with the lamp and screen. Has a convex lens conjugate foci?

Leaving the lamp and screen in position, move the lens into another position between them where it will project a clear image of the lamp on the screen. Explain. What difference do you observe in the two images?

If the lighted lamp be placed at the principal focus of the lens, what is the shape of the refracted wave-front? Is an image formed in this case?

Can you place the lamp in a position where its image will be virtual? Explain.

Calling S in Fig. 107 the position of the lighted lamp, tell how it is placed with reference to the principal focus of the lens.

Where would you place the lamp in order to have its real image as large as possible?

* Convex lenses sold as reading glasses answer well for this experiment. One of about 4 inches in diameter is most convenient.

Where, in order to have its virtual image as large as possible?

In what respects do the images of convex lenses resemble those of concave mirrors?

Refraction by Concave Lenses.

LABORATORY EXERCISE 129.—Let a beam of sunlight pass through a small hole in a screen and fall upon a piece of white paper. Note the size of the spot of light and then place a concave lens* in the path of the beam between the screen and the paper. What change do you observe in the spot of light on the paper? Explain.

Try whether you can project an image of the lighted lamp by means of a concave lens. Look through the lens at the lamp. Do you see a virtual image? If so, is the image nearer to or farther from the lens than the lamp? Explain.

Draw a figure showing the passage of a spherical wave-front through a plano-concave lens.

TOTAL REFLECTION

Cause of Total Reflection.—In Fig. 109 is shown the projection of a spherical wave-front from the source S refracted by passing into a medium in which its

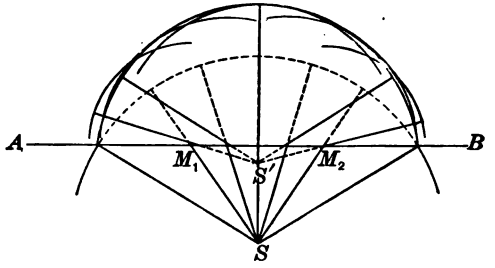


FIG. 109.

velocity is increased one half. It will be seen that while the secondary wave-fronts produced by the middle part of the incident wave combine to form a

*A large spectacle lens answers well for this experiment.

single refracted wave-front, the secondary wave-fronts from M_1 and M_2 lie wholly without the main wave-front at the points of emergence from the refracting surface. It will also be seen that the secondary wave-fronts from points on AB outside of M_1M_2 will lie outside those from M_1 and M_2. It follows that for points on the refracting surface outside the circle whose diameter is M_1M_2 the secondary wave-fronts will not combine to form a continuous wave-front, and that consequently no wave-front from S will emerge except within this circle.

Experiments on Total Reflection.

LABORATORY EXERCISE 130.—Lay a coin in a large, shallow dinner plate near the side farthest from you and pour water over it until the plate is nearly full. Then look at the coin while you lower your eye nearly to the level of the water surface. If the plate is wide enough, the coin will disappear from view before it is hidden by the side of the plate.

If a very broad, shallow vessel be used, a row of coins may be placed in the line of sight, and as the eye is lowered the farthest coins will disappear first.

This experiment shows that the light from the coin can emerge from the water only for a definite distance on any side of the coin.

Fill a round-bottomed, smooth goblet or wine glass with water, and look downward through the water and the sides of the vessel at objects outside the vessel. You will be able to see readily through a circular area near the bottom, but not through the sides near the top.

Since in the experiment with the coin in water light from the coin must strike the whole surface of water in the plate, the question naturally arises as to what becomes of the light which cannot emerge from the water into the air. To answer this question, lay the glass cube used in former experiments upon an ink cross marked upon white paper. Looking downward through the glass you can see the cross plainly. Can you look through one side and the bottom and see the cross?

Can you look through the top and one of the vertical sides and see objects outside the cube?

Since the light which enters the bottom of the cube cannot pass out through one of the vertical sides, it would seem that it must be either reflected or absorbed by the side. Can you, by looking through the top, see evidence that the light from the cross is reflected from the sides of the cube? Does this reflection take place from all the four sides?

Can you hold the cube in such a position that light will pass through two sides at right angles to each other?

In ordinary reflection a part of the light passes through the reflecting surface. In these experiments, since none of the light passes through the reflecting surface, the reflection is said to be Total.

Can total reflection take place when light enters a medium in which its velocity is decreased?

REFRACTION BY TRIANGULAR PRISM

Change in Direction of Wave by Triangular Prism. —In Fig. 110 is shown the change in direction of a light wave in passing through a triangular prism whose refractive index is 1.5. It will be seen that on enter-

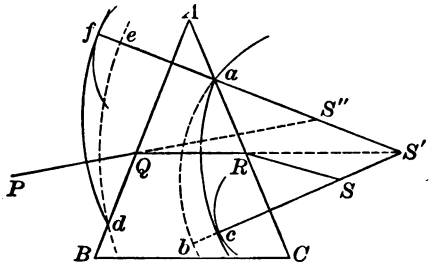


FIG. 110.

ing the prism the wave-front is changed from arc *ab* with its center at *S* to arc *ac* with its center at *S'*. The wave-front accordingly advances through the prism as if its source were *S'*, but upon emerging again

into the air its convexity will be increased, and it will advance as if its source were S''. To an observer at P the source S will accordingly appear to be at S'', and the broken line $PQRS$ will represent the path of a ray of light from S to P.

To Trace the Path of a Ray through a Triangular Prism.

LABORATORY EXERCISE 131.—Draw an ink line on one side of a triangular glass prism parallel to the edges of the prism. Set the prism on end on a sheet of paper and draw its outline with a pencil, as ABC in Fig. 110. Mark the foot of the ink line on the paper, as R. Stick a pin upright to one side of the prism, as at S, and looking through the prism from the other side, stick a pin P where it seems to be in a straight line with R and S. Stick a third pin at Q, where the line PRS leaves the prism. Remove the prism and draw PQ, QR, and RS.

The virtual image of the pin which you see on looking through the prism will then appear in the line PQ produced.

DISPERSION OF LIGHT

Dispersion by Triangular Prism.

LABORATORY EXERCISE 132.—Cut a slit about one millimeter wide in a piece of thin sheet metal or smooth cardboard,* mount it upright on a board, cover it with red glass and set it in front of a window and reflect a beam of sunlight upon it with a mirror or a heliostat. Set a prism parallel to the slit in the path of the beam of red light, and place a ground-glass or paper screen at a distance of about a meter from the prism to receive the colored image of the slit. Notice the displacement of the red image of the slit due to its passage through the prism. Mark on the screen the boundaries of this image.

Without moving the prism or screen, remove the red glass from the slit and replace it by a piece of blue glass, and mark again the boundaries of the image.

Which is more refracted, red light or blue light?

* Such a slit is most easily cut with a sharp chisel.

Remove the colored glass and note the image made by the uncolored sunlight. Are the red and blue images in their former positions? What other colors can you distinguish, and what are their orders of refraction?

Which colored light has been most retarded by its passage through the prism? Which color has been least retarded?

Was the light which passed through the red glass colored by the glass, or does the sunlight contain red light? What became of the other colors when the red glass was interposed?

The Spectrum.—The colored band of light produced by the overlapping images of the slit is called a Spectrum. If the slit be made very narrow, so that each colored image is very narrow, the images will not overlap so much, and each part of the spectrum is said to consist of a pure color. Seven of these so-called primary colors are easily distinguished and are named in their order, beginning with the color most refracted, Violet, Blue, Peacock, Green, Yellow, Orange, Red. No sharp dividing line can be drawn between adjacent primary colors, as in every case the color changes gradually from one to the other.

Recombination of Spectrum.

LABORATORY EXERCISE 133.—With the apparatus arranged as before, place a glass cylinder or round bottle about two inches in diameter filled with water in the path of the spectrum where it is about a centimeter wide. This cylinder will act as a converging lens to refract the diverging light toward a central line. Hold a piece of white paper back of the cylinder to receive the light, and adjust the position of the paper until the line of light upon it is as narrow as possible.

Does the re-combination of the spectrum produce ordinary sunlight?

Newton was the first to prove that the sunlight is made up of a combination of lights of different color, and that these colors are refracted by different amounts in passing through a prism.

Complementary Colors.

LABORATORY EXERCISE 134.—A glass cylinder such as was used in the preceding experiment has black paper, cut as in Fig. 111, pasted upon one of its sides. Place this cylinder filled with water in the path of the diverging spectrum with the paper on the side toward the prism. Adjust it parallel to the prism, and allow the spectrum to fall upon it half above and half below the line *AB*. The spectrum should be about a centimeter in width at the cylinder.

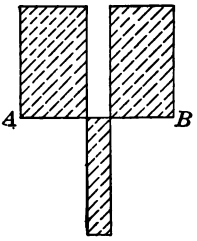


FIG. 111.

It will be seen that precisely the same part of the spectrum is allowed to pass through the slit above *AB* that is cut out by the strip below *AB*. Place a paper back of the cylinder where the colors are combined upon it as in the former experiment. You will now have differently colored lines above and below *AB*. The two colors obtained at one time are such that when combined they will produce ordinary sunlight. They are accordingly called Complementary Colors. They are not the primary colors of the spectrum, but each is made up of the combined colors of a part of the spectrum, while the other is made up of the combined colors of the rest of the spectrum.

Name three pairs of complementary colors.

Color of Bodies.—Since we can see non-luminous bodies only by the light which they reflect to the eye, all the possible colors of bodies must exist in ordinary sunlight. In general, bodies do not reflect equally well all the colors of the sunlight which falls upon them. Usually some of the light enters the bodies and is absorbed, while another part is reflected. In this case, the color of the body is the color resulting from the combination of the primary colors which it reflects, and is complementary to the colors which are absorbed.

Sometimes bodies absorb one part of the light, transmit another part, and reflect a third part. Such

bodies seem of different color when seen by transmitted light than when seen by reflected light. A little ordinary red ink in a glass of water usually shows a different color when we look through it at the light than when seen by reflected light.

Color is accordingly a property of light. Most bodies seem colored on account of their selective absorption of light. Most vegetable bodies contain chlorophyll, which is a great absorber of red light, hence the light which we receive by reflection from these bodies is the complementary color of the red light absorbed.

Dispersion in Lenses.

LABORATORY EXERCISE 135.—Cut a square hole in a piece of thin metal or cardboard, cover it with red glass, and light it strongly by means of reflected sunlight or a lamp placed near it.

By means of a convex lens placed on the side opposite the light, project a sharp image of the square hole on a screen of white paper. When the screen is placed in position to give the sharpest possible image, replace the red glass by a piece of blue glass. Must you move the screen nearer to or farther from the lens in order to project a sharp image by blue light?

Is the focal length of the lens for red light greater or less than for blue light?

Remove the colored glass and see if you can project an image of the hole where it will be surrounded by a red band. Where it will be surrounded by a blue band.

What proofs have you of dispersion in lenses?

Chromatic Aberration.—The defect in lenses which you have just observed is called Chromatic Aberration. Since refraction is always accompanied by dispersion, it is impossible to construct a simple lens of a single substance which will not show chromatic aberration.

It has been found, however, that dispersion is not

proportional to refraction. Some prisms produce a much broader spectrum for the same amount of deviation of the refracted beam than do others. Thus if prisms made of crown glass and flint glass produce exactly the same amount of deviation for red light, the flint-glass prism will produce a greater deviation of the blue light. If these prisms be placed together with their bases in opposite directions, a beam of red light will not be refracted in passing through both; but if a beam of sunlight be passed through them, a spectrum will be produced.

On the other hand, if prisms of crown and flint glass be so made that they will produce the same dispersion, the crown-glass prism will produce a greater deviation than the flint-glass prism, and they can be made to refract a beam of light without producing noticeable dispersion.

Achromatic Lenses. — Lenses are corrected for chromatic aberration by using a concave lens of flint glass with a convex lens of crown glass. Such a lens has a much greater focal length than the crown-glass lens alone, since the flint-glass lens is a diverging lens; but by opposing the dispersion of one lens to that of the other the red and blue light may be brought to the same focus. A lens corrected in this way is known as an Achromatic lens.

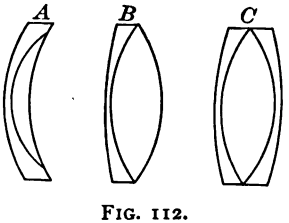


FIG. 112.

In Fig. 112 are shown some of the common forms of achromatic lenses. In every case the convex lens is of crown glass, and the concave lens of flint glass.

INTERFERENCE OF LIGHT

INTERFERENCE BY REFLECTION

Newton's Rings.

LABORATORY EXERCISE 136.—Take two pieces of plate glass with plane, polished faces,* and press them together with a slight rotary motion until they cling together by cohesion. (If the glass faces are not sufficiently plane to make a good contact, breathe upon them and let moisture condense over them and form a surface.) Place the two glass plates in a position where they will reflect light to the eye from their surfaces of contact. If they are sufficiently close together, there will be seen colored bands of light reflected from their surfaces of contact. Fig. 113 is from a

FIG. 113.

photograph of such a pair of plates showing the colored bands.

Increase the pressure upon one edge of the plates by means of the fingers or a clamp, and notice that the colored

* The glass slides used for microscopic work usually answer well for this experiment.

bands seem to surround the place of greatest pressure in more or less regular forms.

Change the pressure, and notice that the bands move as if their position depended upon the distance between the plates.

Lay the plates upon a dark surface in a dimly lighted part of the room and illuminate them by yellow light made by heating common salt on a piece of asbestos or wire in the non-luminous Bunsen flame or in an alcohol flame. Observe that in this case the bands are yellow and black only, and that many more of them can be seen than in sunlight.

In one form of the apparatus frequently used for this experiment one of the plates is plane and the other is a convex, spherical surface of large radius. With this form of apparatus the plates touch in only one place, and the bands are seen to surround this place of contact in more or less symmetrical rings. This is the form in which the apparatus was first used by Newton, and the colored bands were accordingly known as Newton's Rings.

Notice that at the place of closest contact of the plates a dark spot is formed, and that this is surrounded by alternate yellow and black bands. As the plates become farther and farther apart, these bands become closer together. Apparently, wherever the two surfaces are at a certain distance or some multiple of this distance apart, the light reflected from one surface quenches the light reflected from the other surface, while at intermediate distances apart the light from both surfaces combines to increase the intensity. The bands are accordingly called Interference Bands.

Comparison with Sound Interference.—In the experiments on Sound, page 219, you saw that a sounding tuning fork when moved toward and from a reflecting wall had its sound weakened or strengthened by the sound waves reflected from the wall, according as its distance to the wall and back was an uneven or an even number of half wave-lengths.

If we suppose a row of tuning forks of the same pitch standing at an angle to the reflecting wall, as F_1, F_2, F_3, etc., in Fig. 114, where AB represents the line of

the wall, some of these forks will have the intensity of their sound increased and some diminished by the reflection from the wall. A listener walking along the line of forks might notice this variation in intensity, that is, might recognize interference bands of sound.

Suppose, again, a row of forks of different pitch to be sounded together and all moved toward and from the wall, keeping the line parallel to the wall all the time.

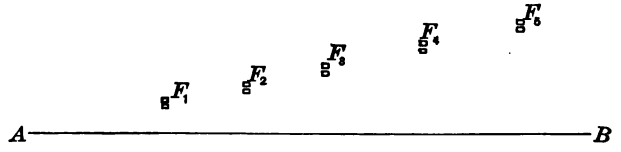


FIG. 114.

In this case, destructive interference would occur at different distances from the wall for different forks, and the resultant sound of the forks would depend upon the distance of their line from the wall. In any position of the forks some of them would have their sound weakened and some strengthened, and the resultant sound would be the sum of the original sounds of all the forks, less the sounds cut out by interference. We would accordingly have sounds of different pitch produced by interference, just as we have lights of different colors produced by interference in the Newton's Rings apparatus.

Theory of Interference.—Our explanation of the formation of the interference bands of light is accordingly as follows:

Let A and B, Fig. 115, represent the two glass plates, and WF a wave-front of light from the source S. Let s_1 and s_2 be points upon the inner reflecting sur-

faces of the two plates which are reached in the same time by the wave-fronts from S. s_1 and s_2 will accordingly be the centers of two reflected waves starting at the same time. These waves will meet in the same phase at some point, as a, on the surface of the plate A, and the point a will be illuminated by both waves. On either side of a one wave-front will be behind the other, the wave-front from s_1 being behind on one side

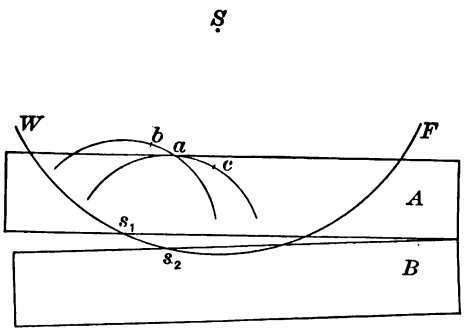


FIG. 115.

and the wave-front from s_2 on the other side. At equal distances on each side of a, as at b and c, the distance between these wave-fronts will be half a wave length of light, and where these points emerge from the glass plate the successive waves will interfere destructively with each other. The point a will accordingly represent the position of a light band, and the points b and c positions of dark bands.

Fig. 116 is made from a photograph of ripples made in mercury by two pointed wires attached to the same prong of a tuning fork so that they will both enter and leave the mercury at the same time as the fork vibrates up and down. The ripples from both vibrating points accordingly start at the same time and spread out in

the form of circular waves just as a light disturbance spreads out from its center in spherical waves. Along the lines where the crest of one ripple meets the crest of another, a row of high ripples is seen, while along those lines where the crest* of one ripple meets the trough of another the surface of the mercury is not thrown into ripples at all. There are accordingly interference

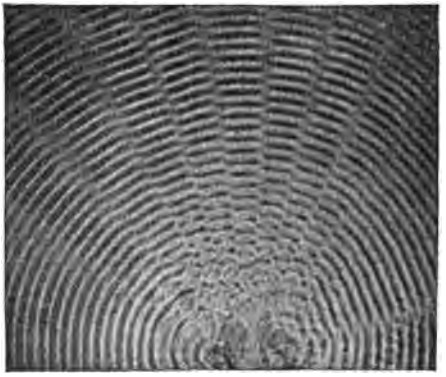


FIG. 116.

bands radiating over the surface which is covered by the two systems of ripples, just as interference bands of light would radiate from s_1 and s_2 in Fig. 115.

If light of many different wave-lengths be used with the Newton's Rings apparatus, then some particular wave length will interfere for each distance of separation of the reflected wave-fronts from the two plates, while other wave-lengths may combine to increase the intensity of their illumination at these same distances of separation. This being true, complete interference bands can be produced only when all the light waves

* The crests of the ripples are shown by the light bands in the photograph.

reflected are nearly of the same length, and the waves of the yellow sodium light made by heating salt in the flame must be all of nearly the same wave-length.

The sunlight, on the contrary, must be made up of many different wave-lengths. When the colored bands are formed by the interference of sunlight, some of these wave-lengths are cut out at every distance of separation of the plates, and the color of the resultant band at any point on the plate must be the resultant of all the colors which are not cut out at that point.

Estimation of Wave-length by Interference.

LABORATORY EXERCISE 137.—Place the interference plates in the sunlight so that the colored bands can be seen, and then hold a piece of red glass so that only the light which has passed through this glass can fall upon the plates and observe the distance between the interference bands. Repeat, allowing only blue light to fall upon the plates. In which case are the interference bands closer together?

Would the interference bands of long waves or of short waves be closer together?

Which apparently has the greater wave-length, red light or blue light?

If all light waves travel with the same velocity, which color, red or blue, is due to the more rapid vibrations?

Periodic Character of Light Waves.—In our earlier discussion of light waves nothing was said about their periodic character, and our only assumption was that these waves are spherical. We have now seen reason to believe that these spherical waves follow each other periodically and very close together. The term wave-length is applied, as in sound, to the distance between the similar phases of two successive waves. Thus, in the circular ripples on the mercury surface a wave-length is the distance measured along the radius of the circle from the crest of one ripple to the crest of the

next one, or from the trough of one ripple to the trough of the next, or from any phase of one to the corresponding phase of the next. The wave-length has no relation to the wave-front. The wave-front of the sunlight at the earth we have already seen is the surface of a sphere of about 93,000,000 miles radius. The mean wave-length of light is about one fifty-thousandth of an inch. That is, these spherical waves follow each other about a fifty-thousandth of an inch apart.

INTERFERENCE BY DIFFRACTION

Diffraction by Narrow Obstacle.

LABORATORY EXERCISE 138.—There are many ways of dividing a wave-front of light into two parts each of which becomes a new source of spherical waves which may interfere with each other, as do the ripples from the two centers of disturbance on the mercury surface. One of these methods is given in the following exercise.

Place in front of a window a screen in which has been cut a vertical slit about one millimeter wide, with smooth edges, and reflect direct sunlight through the slit by means of a mirror or heliostat. At a distance of about a meter from the slit place a vertical wire, as a small knitting-needle or a hat-pin, so that it shall be in the path of the beam of light which passes through the slit and parallel to its edges. At a distance of one or two meters from the wire place a screen of ground glass or greased paper where the light from the slit and the shadow cast by the wire may fall upon it. If the shadow of the wire is in the middle of the image of the slit and is exactly parallel to its edges, this shadow will be seen to be composed of vertical dark and light or colored bands, beginning with a light band in the center of the shadow and having at least two very distinct dark bands, one on each side of the light band. These bands are called interior interference fringes. If your adjustment is good, you will be able to also see interference fringes outside the edges of the shadow, called exterior fringes.

Since the light which passes the edges of the wire seems to be bent, or diffracted, so as to enter the shadow of the

wire, the interference bands seen in the shadow are said to be produced by diffraction.

If we regard the interference bands as produced by spherical light waves having their sources in points on the opposite edges of the wire, the method of their production may be seen from Fig. 117.

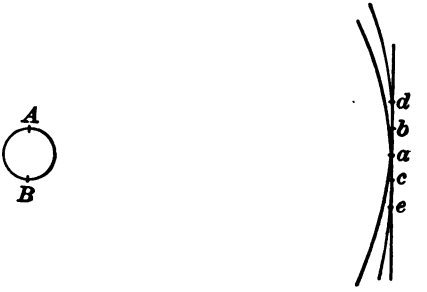


FIG. 117.

Thus, if *A* and *B* represent the points upon the edges of the wire at which two spherical waves originate at the same time, these two waves will meet in the same phase at *a*, and a vertical line through *a* will be illuminated by both waves. At points *b* and *c* one of these waves may be just half a wave length behind the other, as in the case of the reflected wave-fronts from the glass plates in Fig. 115. In this event, the two wave-fronts will interfere destructively at *b* and *c*, and the shadow of the wire will contain vertical dark bands through these points. Outside of *b* and *c*, say at points *d* and *e*, the successive wave-fronts from *A* and *B* will be an entire wave-length behind each other, and points *d* and *e* will accordingly be illuminated by both sets of waves.

If waves of more than one wave-length are sent off from *A* and *B*, the interference fringes will occur at different points for waves of different length; hence only the first pair of dark bands will appear nearly black, while the others will be colored by waves not cut out by interference at that distance from *a*.

Measurement of Wave-length by Diffraction.—A rough measurement of the wave-length of light may be made by the following method:

Let the circle in Fig. 118 represent a cross-section of the wire used in the diffraction experiment, AB representing a diameter and $A'B'$ the width of the shadow of the wire on the screen. Let a be the central light band in this shadow, and b the position of the first interior dark band on one side. Regarding A and B as the sources of the light waves which interfere at b, the distance Bb must be greater than Ab by half a wave-length of light.

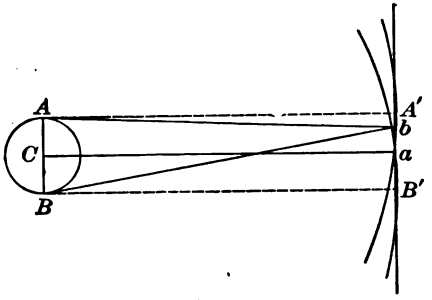


FIG. 118.

Letting $\lambda =$ the wave-length of light, and calling the radius of the wire r, the distance of the wire from the screen $= Ca = d$, and the distance $ab = c$, we have the following equations:

$\overline{Ab}^2 = d^2 + (r - c)^2$ and $\overline{Bb}^2 = d^2 + (r + c)^2$.

Hence $\overline{Bb}^2 - \overline{Ab}^2 = 4cr$.

Also, $\overline{Bb}^2 - \overline{Ab}^2 = (Bb + Ab)(Bb - Ab)$.

$Bb + Ab$ may, for the purpose of the demonstration, be taken as equal to $2d$, and $Bb - Ab = \frac{\lambda}{2}$, hence

$\overline{Bb}^2 - \overline{Ab}^2 = d\lambda = 4cr$, and $\lambda = \frac{4cr}{d}$.

To Measure the Wave-length of Sunlight.

LABORATORY EXERCISE 139.—Place the screen as far from the wire as will allow the interference fringes to be distinctly seen, and with the vernier calipers measure the distance from the outer edge of one of the central dark bands to the inner edge of the other. This distance is $2c$.

With the same calipers measure the diameter of the wire, which is $2r$. Measure d with the meter rule or tape, and calculate λ.

The Diffraction Grating.—A number of very close, equally spaced, parallel obstacles placed in the path of a beam of light, as was the wire in the diffraction experiment, is called a Diffraction Grating. Diffraction gratings are often made by ruling fine, parallel scratches on a glass plate by means of a diamond point.* These scratches disperse the light which falls upon them and thus serve as obstacles to the passage of light, while the clear spaces between them serve as the sources of the secondary waves considered in the interference experiments.

Thus, in Fig. 119, if S_1, S_2, S_3, etc., represent the sources of the secondary waves and the spaces between them represent the obstacles, we have a large number of waves following each other at equal distances and interfering at the same places as would the waves from a single pair of luminous points. The result is to greatly increase the intensity of illumination of the light bands.

Thus at M the pairs of waves starting from equal distances on each side of S_3 will always meet in the same phase and strengthen each other. If m be the

* Gratings suitable for the following experiments can be made by ruling parallel lines on a microscope slide by use of a dividing engine. Gratings having 200 and 400 lines to the centimeter will answer perfectly for these experiments, though finer gratings can be used as well.

position of the first dark band, it is plain that the successive waves will here follow each other at distances of a half wave-length apart. At n, which is the position of a light band, the wave-fronts will be a whole wave-length apart. Accordingly, if light of a single

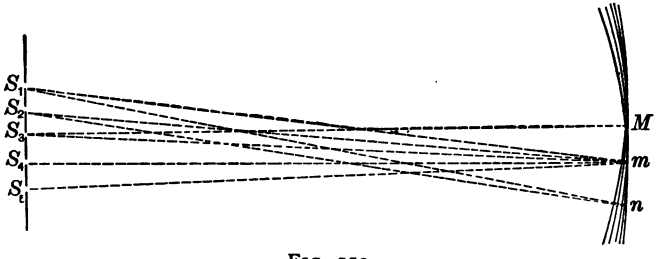


FIG. 119.

wave-length be passed through the grating and a screen placed at a distance in front of it, a series of light and dark bands will appear upon the screen.

If, instead of allowing the light to pass through the grating and fall upon a screen, we hold the grating before the eye and look at a narrow source of light, as the edge of a lamp flame or an illuminated slit, we shall see the successive light bands arranged as they would be upon a screen as far from the grating as the grating is now held from the source of light.

The Grating Spectrum.—If light of different wave-lengths fall upon the grating, the points where the bright bands will appear, as at n, will be different for different wave-lengths. It is plain that since n represents the point where the successive wave-fronts are a single wave-length apart, the shorter the wave-length of the light used the nearer n will lie to M. The grating will accordingly sort out lights of different wave-lengths and arrange them in parallel bands in

the order of their wave-length. Such a sorting will produce a spectrum similar to the prism spectrum.

To observe this spectrum, stand at a distance of several meters from a lighted lamp and look at the edge of the lamp flame through a diffraction grating held near the eye.

Place a red glass in front of the flame or hold it against the grating, and look as before. Notice the distance between the red images of the flame, and then look at it from the same position through a grating having the lines ruled twice as close together. What difference do you observe in the distance between the images?

Measurement of Wave-length by Diffraction Grating.—In Fig. 120, let S_1 and S_2 represent two of the transparent spaces in a diffraction grating, let M represent the central light band on a screen, and n the first light band on one side of the center. Then if S_2c be drawn perpendicular to S_1n, S_1c will equal λ, one wave-length of light.

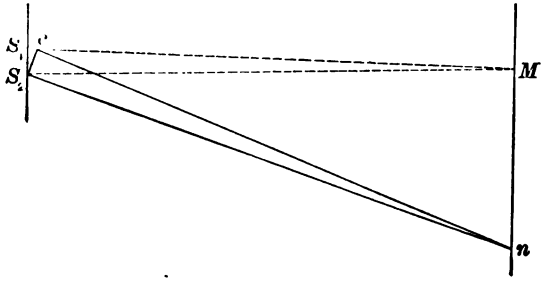


FIG. 120.

Let the distance $S_1S_2 = d$. Then, since S_1S_2 is very small as compared with the distance S_1M, S_1M and S_2M may be regarded as parallel and the angle S_1Mn

may be considered a right angle. We then have the similar triangles S_1cS_2 and S_1Mn, and accordingly $\frac{\lambda}{d} = \frac{Mn}{\overline{S_1n}}$, or by Trigonometry, calling the angle MS_1n the angle Q, $\lambda = d \sin Q$.

To Measure the Wave-length of Sodium Light.

LABORATORY EXERCISE 140.—Place a sodium flame close to and back of a narrow, vertical slit in a darkened corner, place a meter scale horizontal just above or below the slit, and place a diffraction grating at a distance of five or six meters so that you can look through it at the lighted slit. Notice the series of bright bands on each side of the central slit, and locate on the scale the farthest one from the center on each side that you can see distinctly. Divide the distance between these two bright bands by the number of dark spaces between them, and the quotient will give you the distance Mn more accurately than you can measure it between a single pair of bands.

Measure carefully the distance between the grating and the scale for S_1n, and taking the distance d as marked on the grating, calculate λ for the sodium light.

Repeat, using another grating with a different ruling.

Careful measurements by this method will give the value of λ within one per cent of the true value, and measurements giving a value differing more than two or three per cent from the true value should be repeated.

The wave-length of yellow sodium light is .000896 millimeter; if the velocity of light be taken as 300,000,000 meters a second, what number of vibrations a second is required to produce the sodium light?

What is the wave-length of sodium light in glass having a refractive index of 1.5?

RECTILINEAR PROPAGATION

Rectilinear Propagation Due to Interference.—The earlier notion of light propagation was that light traveled in straight lines. We shall now see how this notion arose.

Referring again to Fig. 119, note what would be the

effect of introducing other sources of light midway between S_1, S_2, etc. We see at once that the wave-fronts at n would be only half as far apart, and that a dark band would be at n instead of a light band. The effect would accordingly be to cut out half of the bright images of the flame formed by the grating.

Was this what you observed in looking through the two gratings at the lamp flame? Place a meter stick horizontal just back of the flame and note again the apparent position of the red images of the flame as seen against the scale. Are just half of the images cut out by making the light sources just half as far apart?

Carry this reasoning farther, and you will see that if the light sources were infinitely close together, the first bright image on one side of M would be at an infinite distance from M, or, in other words, if light passes through an opening in which there are no obstacles, it produces only one spot of light on the screen, and this spot is the one, represented in the figure at M, which will be reached by the light from the center of the opening in the least time. All of the light falling upon the screen at a distance from M will be blotted out by interference of other light waves falling upon the same spot. The rectilinear propagation of light is accordingly seen to be an interference phenomenon.

We have seen that the longer the light wave, the farther from M will be its first dark interference band, and accordingly the wider will be the spot of light on the screen about M. Will the spot of light formed on a screen by passing sunlight through a narrow slit be wider when the slit is covered with blue glass or with red glass? Try the experiment with the slit at a distance of several meters from

the screen, one half of the slit being covered with blue and the other half with red glass, or, better, holding the blue and red glasses with their edges together against the side of the screen turned toward the light.

Why are sound shadows not so definite as light shadows?

DOUBLE REFRACTION AND POLARIZATION

Double Refraction in Iceland Spar.—Certain transparent crystals, as Iceland Spar, have the property of separating a beam of light which passes through them in certain directions into two beams which diverge after leaving the crystal. If you hold such a crystal before the eye and look through it at a pin-hole in a piece of opaque paper held against the side of the crystal, you will apparently see two pin-holes, and they will seem at different distances apart according to the direction in which you look through the crystal.

Since the change in the direction of light in passing through the crystal is due to refraction, the two beams must be differently refracted, and the crystal is said to possess the property of double refraction.

One of these beams in Iceland Spar has the same refractive index in any direction through the crystal, as in isotropic bodies, so it is called the ordinary beam. The other beam has a different refractive index in different directions through the crystal, and is called the extraordinary beam. This means, of course, that the light of the ordinary beam has the same velocity in all directions through the crystal, while the extraordinary beam travels with different velocities in different directions. Hence, if a source of light were placed in the center of a crystal of Iceland Spar, there would be two kinds of light waves sent off from it. One of these kinds would consist of spherical waves, as in

isotropic bodies, and the other would be made up of waves having different velocities of propagation in different directions. In the case of Iceland Spar the extraordinary waves are of the shape of oblate spheroids, having their shortest diameter the same as that of the corresponding spherical waves. Accordingly, there is one direction through the crystal in which both sets of waves travel with the same velocity, and hence a beam of light passing through the crystal in that direction will not be doubly refracted. In all other directions the extraordinary waves travel with a greater velocity than the ordinary waves.

Double Refraction in Tourmaline.—The ordinary and extraordinary waves produced by double refraction must differ in some important property to account for the difference in their method of propagation. In order to study their properties separately it is desirable to have some method of isolating them. For this purpose the Tourmaline Tongs are frequently used.

Tourmaline is, like Iceland Spar, a doubly refracting crystal, but it possesses the additional property of absorbing the ordinary waves, so that a section of the crystal of a thickness of a little more than a millimeter will absorb the ordinary waves completely and allow only the extraordinary waves to pass through it. The tourmaline tongs consist of two sections of tourmaline crystal cut of such a thickness as to absorb the ordinary beam, and mounted parallel to each other in a wire handle.

Polarization by Double Refraction.

LABORATORY EXERCISE 141.—Hold the tourmaline tongs in front of the eye and look through both crystals at a lighted window. Turn one of the crystals in its ring until the greatest possible amount of light passes through both. This

light is colored because tourmaline is a colored crystal and transmits only light of certain wave-lengths.

Holding one crystal fixed, rotate the other until no light passes through the two. You will find by careful observation that you must rotate the crystal through just ninety degrees to accomplish this. Notice that the light will pass through either crystal alone when rotated in any direction.

We have now seen that when light has been passed through a tourmaline crystal its properties have been changed so that another crystal may or may not transmit it according as the crystal is rotated around the beam of light as an axis. Since the light which passes through tourmaline is the extraordinary beam produced by double refraction, we find that this beam differs from ordinary sunlight in other respects besides having a differently shaped wave-front. Since tourmaline transmits the extraordinary beam and absorbs the ordinary it must be that when the light passes through both crystals it is an extraordinary beam in both. When one crystal has been rotated through ninety degrees, the beam of light which before entered it as an extraordinary beam apparently enters it as an ordinary beam, and is absorbed by the crystal. By looking through one of the tourmaline crystals at the two images of the pin-hole seen through the Iceland Spar, you will see that by rotating the tourmaline you can cause it to cut off the light from either the ordinary or the extraordinary beam of the Iceland Spar. It would accordingly seem that an extraordinary beam in a crystal can be changed to an ordinary beam by rotating it around the line of propagation through ninety degrees, and *vice versa*.

Light Waves Due to Transverse Vibration.—We can explain this phenomenon only by supposing light to be due to waves of transverse vibration, instead of waves of compression and rarefaction as in sound. Thus, in ordinary sunlight there are waves vibrating in all directions at right angles to the line of propagation of the light. In a doubly refracting crystal, all of these waves except those vibrating in two directions at right angles to each other are apparently quenched.

Then the waves which vibrate in one direction travel faster in certain directions than those vibrating at right angles to them. In tourmaline one set of these waves is absorbed before they have penetrated far into the crystal, while the others pass through and emerge with their vibrations all perpendicular to one plane. Such light is said to be Plane-polarized.

Polarization of Hertzian Waves.—An analogous phenomenon has been observed in the electric waves sent off from the spark discharge of an electric machine or Leyden jar. When these waves are passed through a thick wooden plank they are found to be plane-polarized, just as light waves are polarized in passing through a section of tourmaline. The vibrations of the electric waves in the plank can apparently take place only lengthwise or crosswise of the grain of the wood. When electric waves enter the plank each one is apparently separated into two waves, one of which has all its vibrations parallel to the grain of the wood, while in the other the vibrations are all perpendicular to the grain of the wood. One of these waves is propagated with a greater velocity than the other, and one is absorbed more rapidly than the other. Accordingly, after the waves have passed through a sufficient thickness of the wood only one set emerges. If another piece of plank with its grain parallel to the first be interposed in the path of the wave, it will pass through this plank also. If the second plank have its grain crosswise to the first, it will absorb the waves which have passed through the first plank. Electric waves are accordingly plane-polarized by passing them through a wooden block perpendicular to the grain of the wood.

If the waves are passed endwise through the block,

so that their vibrations must all be perpendicular to the wood fibers, they are not doubly refracted. In the same way, there is one direction through Iceland spar and tourmaline crystals in which double refraction does not take place. This direction is called the Optic Axis of the crystals. Sections of crystal prepared for producing double refraction are cut parallel to the optic axis, just as boards are sawed parallel to the fibers of the wood.

Polarization accordingly teaches us one more fact about the nature of light waves and electric waves, viz., that in these waves the vibrations are transverse to the direction of propagation as in waves on the surface of water, and not parallel to this direction, as in sound waves. Thus, when a spherical wave is set up in the Luminiferous Ether, the vibrations of the Ether particles are everywhere perpendicular to the radii of the sphere, and accordingly parallel to the wave-front.

Polarization by Reflection.

LABORATORY EXERCISE 142.—Lay a piece of glass upon the table, preferably upon a piece of dark cloth or paper, and stand a lighted candle near it. Then, standing at a distance of a few feet from it, look at the reflection of the candle flame in the glass while you rotate one of the tourmaline crystals before your eye. Is the reflected light partly polarized? If not, change your position until you see the image of the flame partly quenched by the rotation of the tourmaline. Observe that the amount of polarization depends upon the angle at which the light falls upon the glass. Estimate as nearly as you can the angle at which the light is most completely polarized.

Theory of Polarization by Reflection.—When a beam of ordinary light falls upon a reflecting surface the Ether vibrations are supposed to be in any or all

directions perpendicular to the path of the beam. Some of them are accordingly parallel to the reflecting surface, while others at right angles to these are approximately perpendicular to it. It is believed that one of these sets is more readily reflected than the other, while the other set more easily penetrates the glass. The reflected beam accordingly has more vibrations in one of these directions than did the incident beam, while the light which penetrates the glass has a corresponding excess of light polarized in the other direction.

It is generally believed that the light polarized by reflection has its vibrations parallel to the glass surface, while the light which passes through the glass has its vibrations perpendicular to these; but the actual direction of vibration cannot be definitely ascertained.

If a number of glass plates be bound together making several reflecting surfaces parallel to each other, a much larger proportion of the incident light may be reflected and polarized by them than by a single plate. The thin glass strips sold for microscopic cover glasses are well adapted to this purpose. If you have such a polarizer, mount it in a vertical position and allow the light of a lamp or candle to fall upon it at the angle of most complete polarization and observe with the tourmaline that the light transmitted through the polarizer is polarized at right angles to the reflected light. Notice that when the light is made to pass through a red glass before falling upon the polarizer it is more completely polarized than when ordinary uncolored light is used. This is due to the fact that the angle of reflection for complete polarization is different for different wave-lengths, and it is only when monochro-

matic light is used that complete polarization can be obtained by reflection.

THE NATURE OF LIGHT

Visible and Invisible Radiation. — In our first experiments on Light we found it to be a form of radiation propagated in spherical waves in an all-pervading medium called the Luminiferous Ether. By means of interference phenomena we were able to show that these waves follow each other periodically at very small distances apart. From the phenomena of polarization we have learned that they are waves of transverse vibration. We have also learned of other forms of radiation which are not visible to our eyes, as the radiation from a heated body which is not luminous, and the radiation from an electric spark or from an electric discharge through a vacuum tube. All of these forms of invisible radiation except the X-Radiation of Roentgen, the velocity of which has not been measured, are known to be propagated with the velocity of light, and are capable of reflection, refraction, interference, and polarization, as are ordinary light waves. They are accordingly waves of transverse vibration in the Luminiferous Ether, and are different from light waves only in having a greater wave-length.

Relation of Visibility to Wave-length of Radiation. —The longest waves of visible radiation are less than .0008 millimeter in length, but if the spectrum of the Sun be thrown upon a screen and its heating effects be studied by means of a delicate thermometer, they will be found to extend far beyond the red end of the spectrum. The invisible radiation at this end of the spectrum is made up of longer waves than the visible

spectrum, and is known as the Infra-Red spectrum. By means of delicate apparatus the infra-red spectrum has been detected to a wave-length of about .025 millimeter.

If a photographic plate be exposed to the solar spectrum and suitably developed, the plate will be found blackened by invisible radiation beyond the violet end of the visible spectrum. The shorter waves at this end of the spectrum are known as Ultra-Violet. While the shortest wave of visible radiation is about .0004 millimeter in length, the ultra-violet spectrum has been photographed to a wave-length of about .0001 millimeter.

The visible radiation is accordingly but a small part of the total radiation of the sun. Thus, if a grating spectrum of the Sun be thrown upon a screen at such a distance that the visible spectrum is four inches long, the known ultra-violet spectrum will likewise be four inches long and the known infra-red spectrum will be twelve feet long.

In terms of the musical notation used in describing sound vibrations, the total known spectrum of the Sun consists of about eight octaves. Of these, two belong to the ultra-violet spectrum, one belongs to the visible spectrum, and five belong to the infra-red spectrum.

The shortest electric waves which have yet been studied are about six millimeters long, and are accordingly about eight octaves below the longest known infra-red waves.

Unknown Nature of Roentgen Radiation. — All attempts at measuring the wave-length of the Roentgen radiation have failed. This radiation has not yet been regularly reflected, refracted, nor polarized. It is

accordingly a mere matter of speculation as to the place which these waves would occupy in the spectrum could they be dispersed by a prism or a grating. Since they resemble ultra-violet radiation in some of their properties, they are supposed by some physicists to be very short waves beyond the ultra-violet end of the spectrum.

The Becquerel Radiation.—Besides the Roentgen radiation there are several other known kinds of invisible radiation which are capable of producing fluorescent or photographic effects. One of the best known of these is the form of radiation given off by the metal Uranium and some of its compounds as well as by a number of other so-called "Radioactive" substances, and called after its discoverer the Becquerel Radiation. It is similar in its properties to the Roentgen radiation and its wave-length is unknown.

Electro-magnetic Origin of all Radiation.—Maxwell's theory of the electromagnetic origin of all radiation is now generally believed. According to this theory light waves are caused by vibration of electrically charged atoms or parts of atoms, and are transmitted by the electric elasticity of the Luminiferous Ether. It is not known that the Ether has any other kind of elasticity, or that it can be set in vibration by anything but electric charges.

PROPERTIES OF THE ETHER

Properties Inferred from Nature of Radiation.—It is principally from the phenomena of radiation that we learn of the properties of the Luminiferous Ether. We know that it is a medium which exists throughout the entire known physical universe, for our only knowledge of the heavenly bodies is obtained through radiation.

It also permeates all known transparent bodies, since these transmit radiation with a greater velocity than would be possible from the properties of the bodies themselves. If light were transmitted by glass instead of by the Ether in glass, its velocity would depend upon the elasticity and the density of glass, as does the velocity of a sound wave; but the velocity of light through glass is about 40,000 times the velocity of sound in the same medium.

We know also that the Ether is capable of transmitting transverse vibrations, hence it must have properties analogous to those of a solid body. The most common conception of the Ether is that it is a jelly-like substance having an elasticity much greater in proportion to its density than any known material body, and allowing the atoms of material bodies to pass through it without appreciable resistance. It seems, however, to exert a pressure upon the atoms of bodies as it also does upon bodies having an electric charge, and it is generally supposed that cohesion and gravitation are due to Ether pressures upon the atoms of material bodies. This being the case, the Ether itself would not be subject to gravitation and hence would not have weight.

SPECTRUM ANALYSIS

Emission Spectra.—We have seen in our experiments on dispersion that different sources of light give different spectra. Thus, while a lamp flame gives a spectrum showing nearly the same color as the Sun's spectrum, the sodium flame gives a spectrum having no colors in it but yellow. When the sodium flame is observed through a prism or a grating only a yellow

image of the slit is seen. If the slit be narrow, this becomes merely a yellow line; but if the slit be very narrow and the image be magnified by a lens, it will be seen to consist of two yellow lines very close together. These lines are the two images of the very narrow slit made by two kinds of yellow light of nearly the same wave-length.

Characteristic Spectra of the Elements.—If the flame be colored with lithium instead of sodium, a red line is seen instead of a yellow one. If potassium be heated in the flame, its spectrum will show a red line and a blue one. Thus each particular element gives its own characteristic spectrum when its vapor is sufficiently heated.

Continuous Spectra.—The spectrum of a hot solid or liquid is always a continuous spectrum, that is, it is not made up of separate images of the slit, but of overlapping images.

A heated gas is apparently capable of setting up light waves of certain wave-lengths only, while a heated solid or liquid may set up light waves of all wave-lengths. The spectrum of a lamp flame is accordingly not a gas spectrum, but the spectrum of a heated solid. That is, the light given off by the flame is the light from the solid particles of carbon which are heated to incandescence before they combine with the oxygen of the air. When the combustion becomes complete, the flame becomes non-luminous, as in the alcohol flame or the non-luminous flame of the Bunsen burner.

Radiation Due to Atomic Vibrations.—Since each element has its own gas spectrum, it seems that the vibrations which produce the light waves must be the vibrations of the atoms in the molecule, and not the

vibrations of the molecules themselves. We have already seen reasons for believing that the molecules of a gas are making all kinds of irregular vibrations, striking each other and rebounding in every direction and with all kinds of velocities. Such vibrations would not have the periodic character necessary for producing light waves of definite wave-length. The atoms in each particular kind of molecule seem, however, to have definite periods of vibration. Thus the atoms in the sodium molecule seem to make about 500,000,000,000,000 vibrations in a second. The atoms of lithium vibrate more slowly, while the atoms of potassium have two periods of vibration, one much slower and one much faster than the sodium atoms.*

It is only when the mean free path of the molecules is great enough to allow the atoms to vibrate in their proper periods between the molecular impacts that an element can give its characteristic spectrum. In solids and liquids the molecules seem to be so close together that their impacts are constantly jarring the atoms out of their normal periods of vibration, and hence waves of many different wave-lengths are being given off by different atoms at the same time.

Use of Spectrum Analysis.—Spectrum Analysis is the method of determining the composition of bodies in the gaseous state by means of the spectra which they emit.

The Spectroscope.—The instrument most used for studying the spectra of different substances is known as the Spectroscope. It is shown in diagram in Fig. 121. It consists essentially of a tube carrying an adjustable

* Recent investigations make it seem probable that light waves are produced by the vibrations of the electrons mentioned on pages 165 and 278, rather than by the chemical atoms.

slit, called the collimator tube, as shown at *A*, a prism or grating, as at *B*, and an observing telescope for viewing the spectrum, as at *C*. The collimator tube regularly has a lens at the end nearest the prism to render the rays from the slit parallel before they fall upon the prism, and the telescope is focused so as to give an image of the slit as seen through the prism by monochromatic light. The spectroscope is also frequently provided with another tube, as at *D*, carrying a scale photographed on glass which can be seen in the telescope by reflection from one face of the prism.

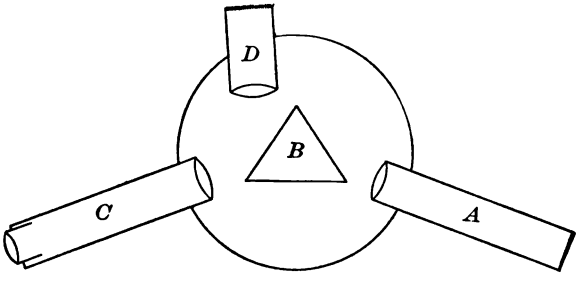


FIG 121.

Absorption Spectra.—We have already seen that colored substances, as red or blue glass, absorb all the light of certain wave-lengths which falls upon them. It has been found that bodies which when heated to incandescence emit waves of a certain length will when cooler absorb waves of the same length, just as a tuning fork will absorb the vibrations sent off by another fork of the same pitch. This is easily shown by the following experiment.*

Light Absorption by Sodium Vapor.

LABORATORY EXERCISE 143.—A glass bulb, as an air thermometer, with a stem of three or four millimeters bore

* It is recommended that this be shown by the teacher.

has a piece of sodium of the size of a grain of wheat and a little gasoline put into the bulb. It is then heated over a flame until the gasoline is boiled away, leaving the bulb filled with gasoline vapor in which sodium will not take fire. The stem is then closed by a piece of rubber tubing and a pinch-cock, and the bulb is further heated in the yellow sodium flame in a dark corner of the room. When the sodium in the bulb boils, its vapor will appear black in the light of the sodium flame, but colorless in the daylight or the light of an ordinary lamp. The light of the sodium flame is completely absorbed by the sodium vapor, while the same vapor is perfectly transparent to light of other wave-lengths.

THE SOLAR SPECTRUM

The Sun's Spectrum not Continuous.—The Solar Spectrum when seen by the naked eye through an ordinary prism or grating seems continuous. We accordingly conclude that sunlight has its source in a very hot solid or liquid body. But if the Sun's spectrum be observed by means of a spectroscope with a very narrow slit and a telescope of sufficient magnifying power, the spectrum will be found to contain many dark lines, showing that certain wave-lengths of light are absent from it.* Thus, at the particular wave-length of sodium light a dark line is seen, indicating that there is no light of this wave-length in the solar spectrum.

Fraunhofer's Lines.—The dark lines of the solar spectrum are called Fraunhofer's Lines because they were first described by Fraunhofer, though some of them had been previously observed by Wollaston. Thousands of these lines can be seen when the spectrum is highly magnified, and nearly all of them are found to

*An ordinary direct-vision spectroscope will show these lines, and it is also useful for observing the character of other emission and absorption spectra.

be of the particular wave-length of the gas spectrum of some known element on the Earth. Thus, over two thousand of them are found to agree in wave-length with lines observed in the gas spectrum of iron. If the Sun is a hot solid or liquid, how may we account for these lines?

Theory of the Sun's Spectrum.—The accepted explanation is that the Sun's spectrum is an absorption spectrum, that is, a continuous spectrum from which certain wave-lengths have been absorbed by passing through some gaseous medium between the Sun and the Earth. The only known gaseous media which may be concerned in this absorption are the atmospheres of the Sun and of the Earth. That part of the absorption which cannot be caused by the Earth's atmosphere is accordingly attributed to the atmosphere of the Sun. Presumably, many of the elements which are in the solid or liquid state upon the Earth are heated above their boiling point on the Sun, and their vapors constitute the Sun's atmosphere, as air and water vapor make up the main part of the Earth's atmosphere. In passing through this cooler vapor, some of the light from the Sun's surface is absorbed, just as the light of the sodium flame is absorbed by the cooler sodium vapor. By this means, we conclude that sodium vapor exists in the Sun's atmosphere, and hence that the element sodium is found in the Sun.

This theory is further strengthened by the fact that the bright, flame-like projections around the edge of the Sun's disc give the bright-line spectra of gases, and that these bright lines correspond in wave-length with the dark lines in the absorption spectrum of the Sun.

Composition of the Sun.—The spectroscope accordingly enables us to determine the composition of the Sun's atmosphere, and by that means to judge of the composition of the Sun itself. The element Helium was first discovered in the Sun by means of its spectrum and afterwards was found in the Earth. More than half of the known elements have been identified in the Sun's atmosphere.

STELLAR SPECTRA

Absorption Spectra of the Stars.—The stars also have spectra resembling more or less closely the spectrum of the Sun. In the yellowish stars, as Capella, Arcturus, Aldebaran, the spectra are very similar to that of the Sun and in some cases the two are apparently identical. In the white stars, as Sirius and Vega, the absorption lines of the metals seen in the Sun's spectrum are very faint or invisible and the blue and violet parts of the spectrum are much stronger than in the yellowish stars. In some of the stars, especially the stars of Orion, an absorption line appears in the blue which does not belong to any known substance, and which is absent from the Sun's spectrum.

Photographs of Stellar Spectra.—Fig. 122 is from a photograph of the solar spectrum and the spectra of several stars.* The striking resemblance between the spectrum of the Sun and that of Capella is shown by photographing them side by side on the same plate.

OPTICAL INSTRUMENTS

Two Kinds of Optical Instruments.—Certain optical instruments, as the Camera and the Projection Lantern,

* From a plate in Huggins' "Stellar Spectra," through the kindness of Professor W. J. Hussey, of the Lick Observatory.

are used for projecting real images of luminous or illuminated objects, while others, as the Telescope and Microscope, are used as aids to vision.

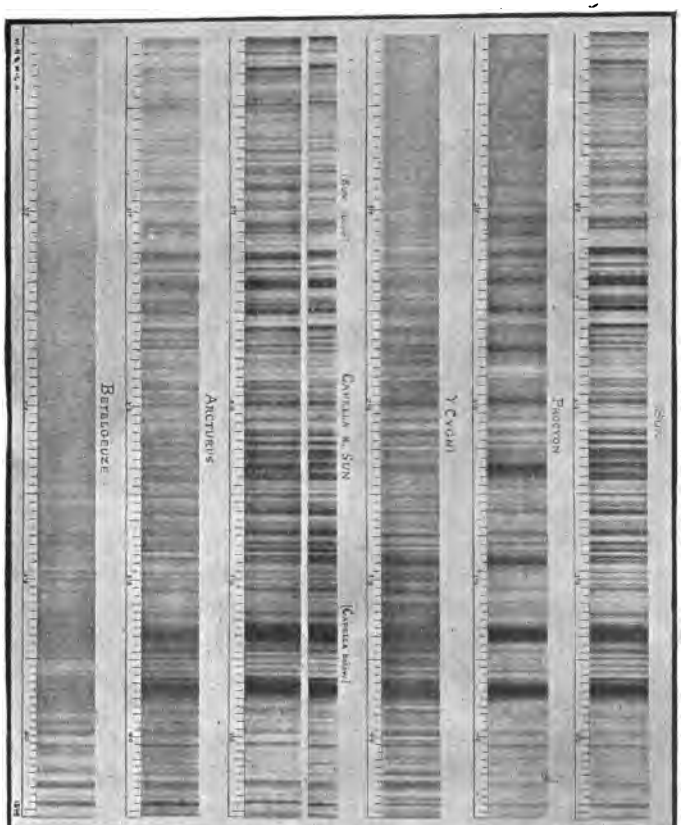


FIG. 122.

The Camera.—The camera will be readily understood from the experiments on refraction through a convex lens. Its essential parts are a converging lens and a screen for receiving the image, while the camera

itself is a dark box arranged to shut out all light except that which enters through the lens. In the camera the image is usually formed at the nearer conjugate focus, while the object is at the more distant focus. The photographic camera is provided with some device for exposing the sensitized plate or film where the image to be photographed is focused upon it.

The Projection Lantern.—In the projection lantern, the object, usually transparent and strongly lighted from behind, is placed at the nearer conjugate focus of the lens, while its enlarged image is projected upon a screen at the farther focus.

Since the projected image is much larger than the object, it is much more feebly illuminated, hence a strong source of light is needed in a projection lantern. The best light for this purpose is the electric arc or the lime light, made by heating a piece of lime to incandescence by means of the hydrogen and oxygen flame.

The Eye.—The human eye, regarded as an optical instrument, is essentially a camera with its lenses so adjusted as to form real images of external objects upon a sensitive membrane, called the Retina, which lines the back part of the eye. The box of the camera is composed of a tough, fibrous, opaque coat, called the Sclerotic Coat, in the front of which is the transparent membrane called the Cornea. The sclerotic coat is lined with a black membrane called the Choroid Coat, which prevents internal reflections, and upon the inner surface of which the retina is spread out.

The cavity back of the cornea is filled with a watery fluid, making of this part of the eye a converging lens. Back of this water-lens lies the Crystalline Lens, a double convex lens having a refractive index about

equal to that of glass. Back of this lens, the main body of the eye is filled with a jelly-like substance having the same refractive index as water, and which serves to preserve the shape of the eye.

In front of the crystalline lens is the Iris, an opaque curtain with a circular aperture in the center, called the Pupil, which can be opened or closed to regulate the quantity of light received by the eye and to aid in correcting the spherical aberration of the lenses.

A section of the eye is shown in Fig. 123, in which

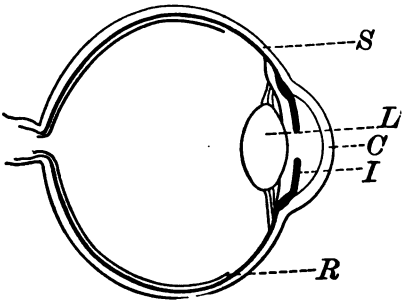


FIG. 123.

C represents the cornea, *L* the crystalline lens, *I* the iris, and *R* the retina.

Since it is necessary in order for distinct vision that the image of the object to be viewed should be formed exactly upon the retina, it becomes necessary to have some method of focusing the eye for near and distant objects. In the ordinary camera the focusing is done by changing the distance between the lens and the screen which is to receive the image; but in the eye the same purpose is accomplished by changing the convexity of the lens, and thus changing its focal length.

The crystalline lens is an elastic body, and is

attached all around its edge by means of muscles to the sclerotic coat. When these muscles contract and pull upon the lens they decrease its convexity and accordingly increase its focal length. This changing of the focal length of the eye to adapt it to vision at different distances is known as the accommodation of the eye.

Defects of Vision.—Since the principal refraction of the eye takes place when the light enters the cornea, the focal length of the eye depends largely upon the convexity of the cornea. If the cornea be too convex, the light from distant objects will be brought to a focus before it reaches the retina, and when the lens cannot be sufficiently flattened by its muscles to correct this defect the eye is said to be near-sighted. That is, only the light from near objects whose wave-fronts are convex can be focused upon the retina. To correct this fault, concave lenses are worn in front of the eye to increase the convexity of the wave-fronts which pass through them before they enter the eye.

If the cornea be too flat, then the light waves from near objects are not brought to a focus until after passing through the retina, hence only distant objects can be distinctly seen. Such an eye is said to be far-sighted. This defect in vision is corrected by wearing convex lenses in front of the eye to decrease the convexity of the wave-fronts from near objects.

Sometimes the cornea is not truly spherical in form but has a greater convexity in one direction than in others. Such an eye is said to be astigmatic, and can be corrected by wearing an astigmatic lens with its greatest convexity at right angles to the greatest convexity of the cornea.

The Simple Microscope.—A single converging lens of short focus is often used as an aid to vision, and is known as a Simple Microscope. Owing to the fact that the lenses of the eye are not free from spherical aberration and do not exactly focus all the rays from a single point in an object to a point on the retina, the image of a point covers a sensible area upon the retina, making a small blur instead of a point. For points which lie very close together these blurs overlap, making an indistinct image. If the object under inspection can be brought very close to the eye so that its separate points have their images farther apart on the retina, this difficulty is partly overcome.

But when an object is held very near to the eye its wave-fronts are too convex to be brought to a focus on the retina. The least distance from the eye at which an object can be distinctly seen without a special effort to accommodate the eye is different in different individuals, but is usually about 25 centimeters, or 10 inches. If the object be brought nearer than this to the eye, its wave-fronts are too convex to be focused upon the retina. The purpose of the simple microscope is to lessen the convexity of the light waves from near objects before they enter the eye.

The Microscope as an Aid to Vision.

LABORATORY EXERCISE 144.—Hold a pin in the fingers, and looking at it closely with one eye, bring it slowly toward the eye. You will find that as the pin approaches very near to the eye it looks much larger and that it also becomes indistinct. It seems larger because its image on the retina is larger than is usually produced by a body of its size, and it becomes indistinct because its image is not brought to a focus on the retina.

Hold a convex lens of short focus, as an ordinary botanical microscope, close to the eye and look through it at the

pin as it is brought near to the eye. You will find that the pin can now be seen distinctly much nearer to the eye than before and that it accordingly seems larger than before. The lens renders the convex wave-fronts from the pin less convex, and the pin can accordingly be seen until it approaches so near the eye that its wave-fronts after passing through the lens are more convex than they would be without the lens if the pin were at the least distance of distinct vision.

Make a pin-hole in a piece of opaque paper, and holding it close to the eye, look through it at the pin as it approaches the eye. You find that in this case also you can see the pin much closer to the eye than before. This is because the small circular area of a wave-front which passes through the pin-hole is not too convex to be focused upon the retina. Observe that in this case also the pin seems magnified.

Hold the lens in front of one eye and the pin-hole in front of the other and look through them at the page of a book held as near to the eye as it can be distinctly seen through the lens. It will be seen that the letters appear almost equally magnified to both eyes. The lens and pin-hole accordingly serve about equally well to correct the spherical aberration of the eye for very convex wave-fronts.

Which seems nearer to the eye, the page seen through the pin-hole or through the lens?

Which is seen more distinctly?

From which does the eye receive more light?

What advantages, if any, has the lens over the pin-hole?

Magnifying Power.—Since the wave-fronts which pass through the lens are rendered less convex than before, they seem to come from farther back of the lens than the object; that is, the apparent distance of the object seen through the lens is the distance of its virtual image. When this virtual image is at the least distance of distinct vision the object cannot be brought nearer to the eye without rendering its image on the retina indistinct.

You saw in looking through the lens and the pin-

hole at the same time that the object seemed equally magnified by both, hence the object seen through the lens has the same-sized image on the retina that it would have with the lens removed. The object seen through the lens seems farther away, however, than it does with the lens removed, and it accordingly appears as large as it would have to be in order to produce the same-sized image upon the retina if it were at the least distance of distinct vision.

Since the more convex the lens, the nearer the object can be held to the eye, it is plain that the magnifying power of the simple microscope is greater the less its focal length.

The Compound Microscope.—The compound microscope is an arrangement of two or more lenses for producing a greater magnifying power than is possible with a simple microscope. Since in practice it is very inconvenient to bring the object as near to the eye as would be necessary in order to see it through a very convex lens, it is customary to place the object to be observed just outside the principal focus of a convex lens of short focus, so that a real image may be formed on the other side of the lens. This real image is then observed through another lens used as a simple microscope. Thus, in Fig. 124, the small convex lens O, called the object lens or objective, forms a real image of the object AB at $A'B'$, and this image is observed through the lens E, called the eye lens, which causes it to seem to be at $A''B''$. In practice both the objective and eye lenses are often made of two or more lenses in order to give a greater convexity than is possible with a single lens. In some of the highest power microscopes the objective system alone consists

of as many as ten single lenses. Part of these are concave lenses, and are used to correct the dispersion of the convex lenses.

The Telescope.—In the compound microscope the object is placed at the nearer conjugate focus of the objective and the image is formed at the farther conju-

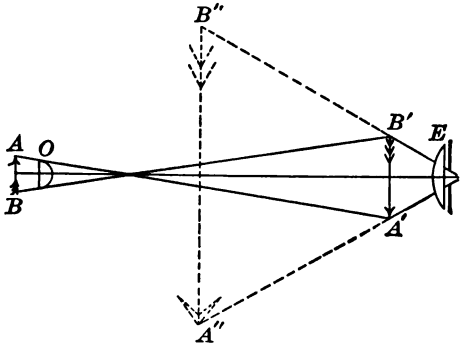


FIG. 124.

gate focus, making the image larger than the object. The image is then apparently further magnified by means of the eye lens. In the telescope the object is at the more distant and the image at the nearer conjugate focus, hence the image is smaller than the object. This image is observed through an eye lens, as in the compound microscope.

Construction of a Microscope and Telescope.

LABORATORY EXERCISE 145.—Place a convex lens between a lighted lamp and a ground-glass or greased-paper screen as in Laboratory Exercise 128. Place the lens so that the lamp is at the nearer conjugate focus, and make the image as distinct as possible upon the screen. Place another convex lens of shorter focus on the other side of the screen where the image can be distinctly seen through the screen when the eye is near the lens. Observe that the image is

larger than the object, and that it is still further magnified by the eye lens. Leaving the lenses in position, remove the screen, and look through both lenses at the lamp. Observe that the image of the lamp is apparently seen in the same position and is apparently of the same size as when the screen was used. The instrument as now arranged is a compound microscope.

Replace the screen, and move the object lens farther from the lamp so that a reduced image is formed upon the screen. Remove the screen, and observe the lamp through the two lenses as before. The instrument is now a telescope. By removing the eye lens, you will observe that the lamp can be viewed through the object lens alone by placing the eye in the proper position, that is, at the distance of distinct vision from the place where the image was formed upon the screen. The eye lens accordingly serves as a simple microscope for viewing the image formed by the object lens.

The Spy Glass.—The telescope arranged as in the preceding exercise is known as an astronomical telescope, in distinction from the terrestrial telescope or spy glass used for viewing objects upon the Earth. Since the real image formed by a convex lens is inverted, the astronomical telescope shows objects inverted. This defect may be corrected by introducing another convex lens between the object lens and the eye lens to re-invert the image formed by the object lens. In the ordinary terrestrial telescopes two convex lenses close together are generally introduced for this purpose because by this means the re-inverted image can be formed in a shorter telescope tube than when a single lens is used.

COLOR VISION

Young's Theory of Color Vision.—We have already seen that lights of different wave-lengths produce different color sensations. We have also seen that by

combining lights of different colors in suitable proportions the sensation of white light may be produced. What we call white light is accordingly not a simple color sensation, but a complex sensation resulting from several simple sensations. Most of the other color sensations are also complex. It was shown by Dr. Thomas Young that any color sensation could be produced by the mixture in suitable proportions of light of three different wave-lengths, and Dr. Young was led from this fact to the theory that in the eye there are produced three simple color sensations which are capable when suitably combined of producing all possible color sensations. These three simple sensations are red, green, and blue-violet.

Color Blindness.—In some persons the eye is incapable of producing more than one or two of these sensations, and then the person is said to be color blind. Thus if a person be red color blind, all the colors he can see are those which may be produced by the combinations of green and blue-violet light.

COLOR PHOTOGRAPHY

Lippmann's Process.—Several methods of so-called color photography have been invented, but so far only one, the process of Lippmann, is true color photography. In this method the sensitized plate or film is placed against a mirror surface, so that the light which falls upon it is reflected back through it again. The advancing and reflected waves then interfere in the sensitized emulsion, producing a set of standing waves with planes of interference and planes of greatest vibration, as in sound waves in a Kundt's tube. If the light be all of a single wave-length, these interference planes

will be parallel and distant from each other by half a wave-length of the light used. Since chemical action takes place in the emulsion of the sensitized plates only where there is no destructive interference, the silver in the plate will be reduced after developing only in these parallel planes distant from each other by half a wave-length of the light used.

If light is allowed to fall upon the plate after it is developed, these parallel planes of silver will act like the reflecting surfaces in the Newton's rings apparatus, but, being at the same distance apart everywhere, the reflection from successive surfaces will strengthen one particular wave-length and weaken all the others. The color which is strengthened will be the one whose wave-length is twice the distance between the reflecting planes, that is, the color by which the plate was originally lighted.

Ives' Method.—Some of the most successful methods of representing objects in their natural colors by means of photography depend upon the discovery of Dr. Young that all colors may be produced from a combination of the three primary colors, red, green, and blue-violet. In the Ives photographic process three negatives are taken simultaneously on the same plate through three color filters each of which allows light of only one of the primary colors to pass. One of the negatives is accordingly blackened where it receives red light from the object, another where it receives green, and the third where it receives blue-violet. Since each color filter absorbs all the light except the one color, the parts of the negative which do not receive light of this color are not blackened at all.

Positives are then printed on glass from these nega-

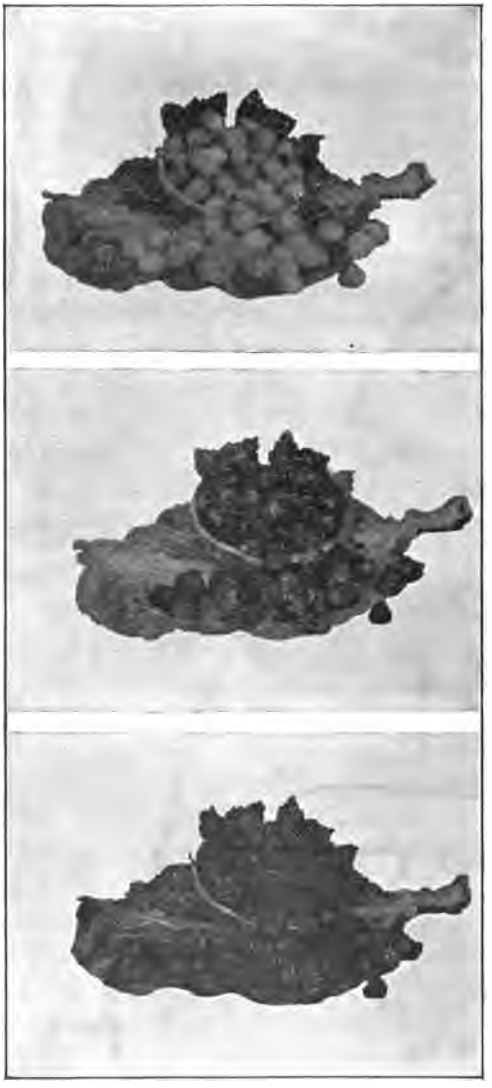


FIG. 125.

tives. Each positive is black except where the negative was illuminated by light of one of the primary colors, but is transparent where it was lighted by its own particular color. If, now, the original color filters be placed over the positives and they be illuminated by white light, one of them will show the red parts of the picture, another the green parts, and the third the blue-violet parts.

Fig. 125 shows three photographs taken through the three color filters. The upper picture, taken through red glass, shows the strawberries white and the leaf black. If looked at through red glass, this will show red berries on a black leaf.

The second photograph is taken through the green filter, and shows the berries black on a white leaf. If looked at through a green glass, this will show black berries on a green leaf.

The third photograph, taken through the blue-violet filter, shows both the berries and the leaf black, but some of the veins in the leaf are white.

If the three pictures be projected upon a screen through the proper colored glasses and superimposed upon each other, the first will give the red berries, the second the green leaf, and the third the bluish veins in the leaf. The resulting picture will accordingly be in its natural colors.

APPENDIX A

Units of Electrical Measure.—At the International Congress of Electricians which met in Chicago in 1893 the following definitions of electrical units were agreed upon, and the units as here defined are known as the International Electrical Units.

The International Ohm, represented by the resistance offered to an unvarying electric current by a column of mercury at the temperature of melting ice, 14.4521 grams in mass, of a constant sectional area and of a length of 106.3 centimeters.

The International Ampere, represented by the unvarying current which, when passed through a solution of silver nitrate in water, and in accordance with the specifications laid down by the committee, deposits silver at the rate of .001118 of a gram per second.

The International Volt is the electromotive force that, steadily applied to a conductor whose resistance is one international ohm, will produce a current of one international ampere.

The International Coulomb is the quantity of electricity transferred by a current of one international ampere in one second.

The International Farad, the international unit of capacity, is the capacity of a condenser which is

charged to a potential of one international volt by one international coulomb of electricity.

The Joule, which is equal to 10^7 ergs, and is represented by the energy expended in one second by an international ampere in an international ohm.

The Watt is the power of a current which does work at the rate of one joule per second.

The Henry, the unit of induction, is the induction in a circuit when the electromotive force induced in this circuit is one international volt, while the inducing current varies at the rate of one ampere per second.

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